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PRACTICAL PHYSICS

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AN AUTOMOBILE ILLUSTRATES SOME PRINCIPLES IN EACH OF THE MAIN DIVISIONS OF PHYSICS

PRACTICAL PHYSICS

FUNDAMENTAL PRINCIPLES AND APPLICATIONS TO DAILY LIFE

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PREFACE

THE chief aim of the first edition of this book was to impress upon teacher and pupil alike that the study of physics is not merely an abstract mental exercise to be patiently undergone in the hope of training one's mind. It is rather a simple, straightforward attempt to understand and to use intelligently a multitude of familiar objects and devices that surround us on every hand. If rightly taught, physics should be the most popular subject in the curriculum; for no satisfaction is more complete than that which comes to a person already familiar with the fundamental principles of some branch of modern science who finds himself habitually and instinctively detecting and appreciating applications of these principles in unexpected places in the course of his daily life.

It was to suggest this point of view that we chose the title PRACTICAL PHYSICS; and the same considerations led us to direct the student's attention chiefly to the familiar objects of everyday life rather than to the subtleties of molecular physics and atomic structure. Although the latter are of the greatest importance and interest to maturer students, they are nevertheless so far outside the experience of those who are approaching the subject for the first time as to seem inevitably more like "book learning" than like real life.

We have pursued the same course in the present revision. In particular we have been responsive to the fact that during the nine years since the first edition appeared, the automobile has ceased to be largely the plaything of the well-to-do, and has become the working tool of multitudes of families in city and country alike. As illustrative material for nearly every division of physics the modern automobile is especially appropriate because of this widespread familiarity on which a physics teacher can build.

The World War has had many notable results, not the least important of which are: *first*, that it awakened a popular interest in and appreciation of physical and chemical science hitherto unmatched in the world's history; and *second*, that it led to an unparalleled concentration of able minds on practical or applied as distinguished from pure or theoretical physics and chemistry. There resulted many new applications of the fundamental principles of these sciences. Of these we have attempted to describe only such as seemed to us important in peace as well as in war; but even the few selected form an important addition to the domain of "practical physics."

We have doubtless included in this book more material than it is advisable for any class to undertake in a single year. This gives the teacher an opportunity to adapt his instruction to local needs and to the time available. We believe that it is most important to *select* carefully just what material can best be used and to teach that *thoroughly*, rather than to try to touch upon many topics superficially.

The present edition is as nearly like our former book in spirit, pedagogical method, and general content as the passage of nine years permits. In particular, we have tried to arrange the material in the most *teachable order*, to give clear and concise *summaries* at the ends of the chapters, to set *practical* rather than artificial *problems*, to minimize the arithmetical drudgery involved in solving them, and to suggest many *questions* designed to get students into the habit of seeking useful information from the mechanics, artisans, engineers, and others whom they meet outside the classroom.

In the details there are, however, a number of improvements in this edition, among which the following may be mentioned.

1. There are about one hundred more illustrations, and more than half of the old cuts have been redrawn for greater clearness and simplicity.

2. The applications of physical principles to the submarine,

the automobile, the airplane, and the airship have been more fully discussed.

3. The subject of electricity has been handled more simply and directly, with special reference to its present-day commercial applications. Radio communication and radioactivity have received more attention.

4. We have greatly increased the number of problems and questions, not expecting that all will be done by any class, but in order to offer more variety and greater opportunity for selection.

5. We have introduced a considerable number of "practical exercises." These may, of course, be ignored by the teacher without disturbing the rest of the course. But if each student's interest can be so aroused that he undertakes with enthusiasm to carry one or more of these independent investigations through to some definite conclusion in the course of the year, devoting spare time to it as to any hobby, and using his own initiative with only occasional informal guidance from the teacher, both his pleasure and his mental gain will be very great.

We are greatly indebted to many teachers who from their experience with the first edition have made valuable criticisms and suggestions for its improvement. Especially would we mention Mr. Edward E. Ford, of the West High School, Rochester, N. Y., Mr. Arthur B. Hussey, of the High School, New Rochelle, N. Y., Mr. A. L. Jordan, of the Technical High School, San Francisco, Mr. H. W. LeSourd, of Milton Academy, Milton, Mass., Mr. M. R. McElroy, of Woodward High School, Cincinnati, and Mr. J. C. Packard, of the High School, Brookline, Mass.

In obtaining material for the new illustrations we have been greatly assisted by Professor George E. Hale of Mt. Wilson Observatory at Pasadena, Mr. Walter B. Littlefield of Boston, Professor Dayton C. Miller of the Case School, Cleveland, Professor Frank A. Waterman of Smith College, and Professors Theodore Lyman, Lionel S. Marks, and Frederick A. Saunders of Harvard University.

Among the firms which have coöperated with us in preparing the text and the illustrations are the following:

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The authors are under special obligations to Dr. D. O. S. Lowell, formerly headmaster of the Roxbury Latin School, for reading the proof sheets, and to Mr. James S. Conant of the Suffolk Engraving and Electrotyping Co., Cambridge, for preparing the illustrations.

N. H. B.
H. N. D.

April, 1922.

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PRACTICAL PHYSICS

CHAPTER I

INTRODUCTION: WEIGHTS AND MEASURES

Why study physics — content and divisions — physics involves measurement as well as description — important units in English and metric systems — density — units of time.

1. Why study physics? Everyone has had something to do with machines of one sort or another all his life. In the household there are sewing and washing machines, vacuum cleaners, and phonographs. On farms people mow, reap, and thresh grain with machines which are often drawn by mechanical horses called tractors; they pump water with windmills or with hot-air, gasoline, or oil engines; they skim milk with a machine called a separator; and even the milking itself is often done by machines. In the city people travel on electric cars and go upstairs on hydraulic or electric elevators; streets and homes are lighted and cookstoves heated by electricity generated by great machines in central power plants. In business and in commerce people are constantly using steam, gas, and electric engines, cranes and derricks, locomotives, ships, and trucks. The telephone, the automobile, and the motion-picture machine, which are now familiar objects, are applications of the principles of physics.

Everyone has used one or more of these devices, and nearly everyone has at times wondered and perhaps discovered how some of them work. That is, almost everyone has already begun to study *physics*, for it is one of the chief aims of physics

to discover all that can be known about such machines as have just been mentioned.

2. Physics a science. The sort of physics that will be found in this book differs from the sort that everyone has been unconsciously studying all his life, chiefly in that it seeks to answer not only the questions "why" and "how," but also the question "how much." It is only when we begin to *measure* things definitely that we get the kind of information that helps us to use them to the best advantage. Thus everyone knows in a vague way that an automobile goes up a hill because the gasoline which is burned in the engine makes it turn the driving wheels, and these in turn push against the road, if it is not too slippery, and thus propel the automobile. The physicist, when he had thought of all this, would go on to ask himself such questions as "How much gasoline does it take, how much ought it to take under ideal conditions, and what becomes of the difference? How much force must be exerted by the brakes to hold the automobile on a hill, how large a brake surface will do this, and how strong must the brake rod be?" When he can answer all these and many other questions, he is in a position to use his machine more effectively, and perhaps to improve its mechanism.

3. Divisions of physics. The object of studying physics is, then, chiefly to learn to think accurately about very familiar things. But these things are so varied in kind that we shall find it convenient to divide the whole subject into five divisions: **mechanics**, **heat**, **electricity**, **sound**, and **light**. For example, suppose we wanted to make a thorough study of the automobile (Fig. 1). Under **mechanics**, we should study about its cranks, gears, levers, pumps, and brakes, including their movements, and the strength of the material of their construction; under **heat**, the engine, carburetor, and radiator; under **electricity**, the spark plug, spark coil, generator, and battery; under **sound**, the horn and muffler; and finally, under **light**, the lamps and their reflectors and lenses. In a

similar way it might be shown that any piece of modern machinery, whether it is an automobile or a locomotive, a motor boat or an ocean liner, an airplane or a submarine boat, is

Fig. 1. Cross section of an automobile. (Compare with Frontispiece.)

not only an embodiment of the principles of physics, but has in very large measure been made possible by the science of physics.

4. Physics begins with measurements. At the very outset we may well recall an old saying of Plato's: "If arithmetic, mensuration, and weighing be taken away from any art, that which remains will not be much." In the laboratory the student will learn to measure many different kinds of things, not mainly for the sake of the results he gets, but rather that all through life he may know a good measurement when he sees one, and may be able to discuss accurately and with confidence the quantitative problems that are always coming up.

It is well to remember that all physical measurements are more or less inaccurate, and that the degree of precision to be aimed at depends on the purpose of the measurement. For example, an error of an inch in determining the distance between two milestones is a much less serious matter than an

error of one one-hundredth of an inch in measuring the diameter of an automobile bearing.

5. Units of measurement. In the United States the value of things that are bought and sold is measured in dollars and cents. Fortunately this system of money is made on the decimal plan, that is, in multiples of ten. Our system of weights and measures, on the other hand, is not a decimal system, and is very inconvenient. Nevertheless, since the pound, foot, quart, gallon, and bushel are still in general use in the United States and in Great Britain, we must be familiar with them. During the last century most of the other civilized nations have adopted the **metric** system of weights and measures, in which the relation of the units is expressed in multiples of **ten.** In scientific work the metric system is almost universally used throughout the world, because it greatly reduces the work in making computations. Therefore it is advisable for us to become proficient in the use of *both* the English and the metric system of weights and measures.

Fig. 2. The international meter bar. The distance is measured between two scratches ruled across the web.

6. Meter and yard. The **meter** is the distance between two lines on a metal bar (Fig. 2) which is preserved in the vaults of the International Bureau of Weights and Measures near Paris.*

Since the length of this metal bar changes a little with the temperature, the distance is measured at the temperature of melting ice. A very accurate copy of the bar is deposited in the United States Bureau of Standards in Washington, D.C., and this copy is the legal meter of the United States.

* It was originally intended that the meter should be equal to one ten-millionth part of the distance from the equator to either pole of the earth, but it is impossible to reproduce an accurate copy of the meter on the basis of this definition. Later measurements have shown that the "mean polar quadrant" of the earth is about 10,002,100 meters.

In the United States the **yard** is legally defined as $\frac{3600}{3937}$ of a meter.

7. Some important units of length. In the problems of physics we shall find that certain units of length are very frequently used. These are given in the following table and should be memorized:

UNITS OF LENGTH

ENGLISH.

1 foot (ft.) = 12 inches (in.)
1 yard (yd.) = 3 feet
1 mile (mi.) = 5280 feet

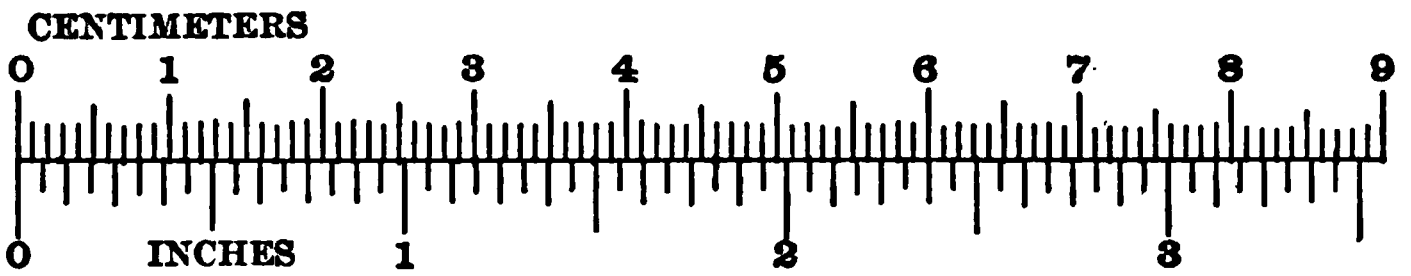

Fig. 3. Relative sizes of the inch and the centimeter.

METRIC.

1 meter (m.) = 1000 millimeters (mm.)
1 meter = 100 centimeters (cm.)
1 kilometer (km.) = 1000 meters
1 inch = 2.540 centimeters (Fig. 3)
1 meter = 39.37 inches

8. Units of area. The unit of area which is most extensively used is the area of a square whose side is of unit length. Thus the area of a city house lot is reckoned in square feet, the unit being a square one foot on each side. In the laboratory, area is often measured in square centimeters (cm^2), the unit being a square one centimeter on each side. It is evident from figure 4 that one square inch is equal to about 6 square centimeters. More accurately, it is 2.54×2.54, or 6.45 square centimeters.

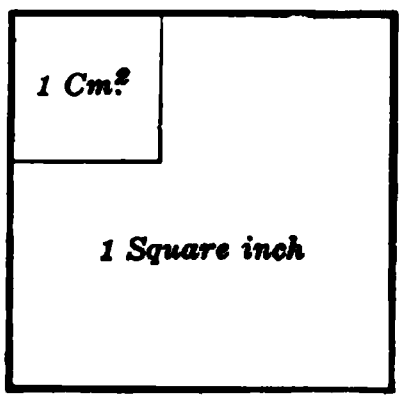

Fig. 4. Relative sizes of the square inch and the square centimeter.

The usual method of determining area is by calculation from the measured linear dimensions. Thus the area of a rectangle or parallelogram is equal to the base times the altitude ($A = b \times h$). The area of a triangle is equal to $\frac{1}{2}$ the base times the altitude ($A = \frac{1}{2}b \times h$). The area of a circle is equal to 3.14 times the square of the radius ($A = \pi r^2$).

9. Units of volume or capacity. The unit of volume that is most extensively used is the volume of a cube whose edge is of unit length. Thus the volume of a freight car is reckoned in cubic feet, the unit being a cube one foot on each edge. In the laboratory we measure the capacity of a flask in cubic centimeters (cm^3). The **liter** is the volume of a cube (Fig. 5) which is 10 centimeters (about 4 inches) on each edge. The **liter** is therefore equal to 1000 cubic centimeters.

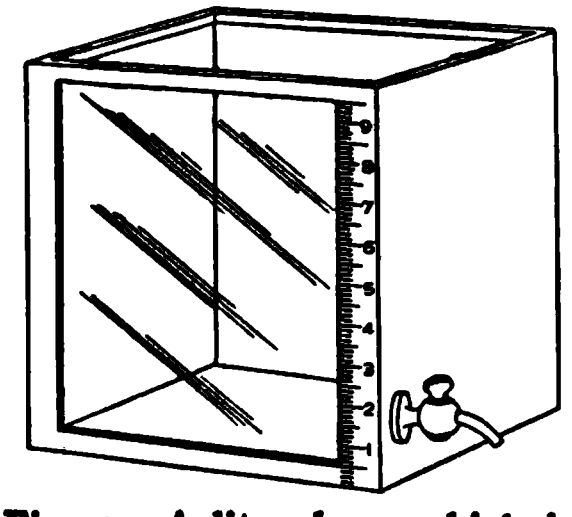

Fig. 5. A liter box, which is a cube 10 centimeters on each side.

UNITS OF VOLUME

ENGLISH.

1 cubic foot (cu. ft.) = 1728 cubic inches (cu. in.)
1 cubic yard (cu. yd.) = 27 cubic feet
1 gallon (gal.) = 4 quarts (qt.) = 231 cubic inches

METRIC.

1 liter (l.) = 1000 cubic centimeters (cm^3)
1 cubic meter (m^3) = 1000 liters
1 liter = 1.06 quarts

The volume of a regular solid is best determined by calculation from the measured linear dimensions. Thus to get the volume of a box, we find the product, length by width by depth. In the case of a cylindrical figure we compute the area of the base (πr^2) and multiply by the height. For measuring liquids we use a graduated vessel of metal or glass. Thus in the English system we have gallon and quart measures, and for small quantities, measures marked in fluid ounces (sixteenths of a pint). In the metric system we have flasks (Fig. 6) and graduates (Fig. 9). A teaspoon holds about 5 cubic centimeters.

Problems

(Give answers to *three significant figures.**)

1. How many centimeters equal 1 foot?

2. How many inches equal 76 centimeters?

3. How many feet equal 1 meter?

4. A boy is 5 feet 6 inches tall. Express his height in centimeters.

5. Express 1 kilometer as a decimal part of a mile. (Remember this number.)

6. The Falls of Niagara on the American side are about 165 feet high. Express this in meters.

7. The diameter of a certain automobile wheel with its tire is 30 inches. How many revolutions does the wheel make (*a*) in going a mile; (*b*) in going a kilometer?

8. An aquarium is 60 centimeters long, 30 centimeters wide, and 45 centimeters deep. How many liters of water will it hold?

9. A cylindrical kerosene can holds 5 gallons. If it is 11 inches in diameter, how tall must it be?

10. A cylindrical quart measure is 6 inches high. What is its diameter?

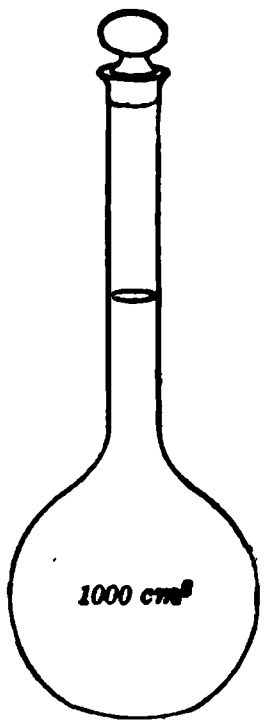

Fig. 6. A flask which holds 1 liter when filled to the mark on the neck.

11. A cylindrical berry box is measured and found to be 6.15 inches in diameter and 2.1 inches deep. What is its capacity in dry quarts? (In the United States a dry quart is 67.2 cubic inches.)

12. A cylindrical jar is 4 inches in diameter and 10 inches deep. How many liters will it hold?

13. A water tank is 2 meters long, 150 centimeters wide, and 80 centimeters deep. How many gallons will it hold?

10. Units of weight.† The **kilogram** is the weight of a certain platinum-iridium cylinder which is preserved with the standard meter near Paris, or that of a very accurate copy of this cylinder

* For an explanation of what is meant by "significant figures" consult your laboratory manual.

† The distinction between weight and mass will be made in section 151.

which is deposited in the United States Bureau of Standards in Washington. It was intended that each of these cylinders should weigh the same as one liter of pure water, although this has turned out to be not quite true. Yet it is nearly enough true for our present purposes. Therefore the **gram**, which is the one-thousandth part of a kilogram, **is the weight of one cubic centimeter of water.** It may be helpful to remember that our 5-cent nickel piece weighs 5 grams and our silver half-dollar weighs 12.5 grams.

In the United States the pound avoirdupois is defined legally as $\frac{1}{2.204622}$ of a kilogram.

Units of Weight

ENGLISH.

1 pound (lb.) = 16 ounces (oz.)
1 ton (T.) = 2000 pounds

METRIC.

1 gram (g.) = 1000 milligrams (mg.)
1 kilogram (kg.) = 1000 grams
1 kilogram = 2.20 pounds
1 cubic foot of water weighs 62.4 pounds
1 cubic centimeter of water weighs 1 gram

11. Weighing machines. The **spring balance** (Fig. 7) is a simple machine for getting the weight of things, or for measuring forces of other kinds, such as the pull exerted by a rope. It contains a coiled spring, and the force exerted is indicated by the pointer on the scale. The spring balance is very extensively used because of its great convenience, and its indications are close enough for many practical purposes.

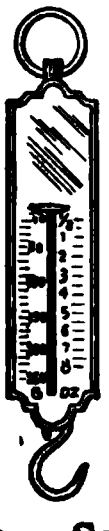

Fig. 7. Spring balance.

The **platform balance** (Fig. 8) consists of a delicately mounted equal-arm balance-beam with a pan supported at each end. The balance is

used to show the equality of the weights of two bodies; that is, two things are said to have the same weight if they balance each other when supported on the ends of an equal-arm balance. The determination of the weight of any object by the platform balance depends upon the use of a set of weights, which may be combined in such a way as to match the weight of the object.

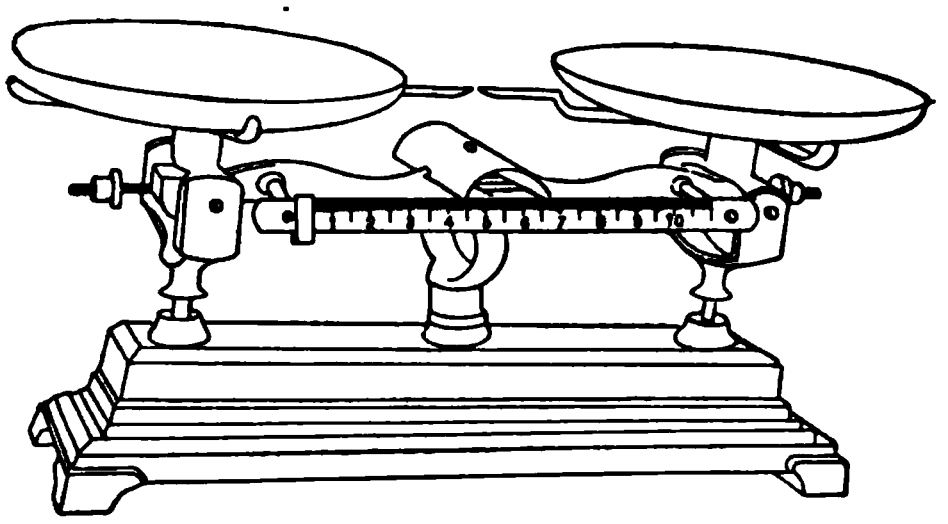

Fig. 8. Platform balance.

Problems

1. How many grams equal 1 pound?
2. How many grams equal 1 ounce?
3. A girl weighs 52.5 kilograms. Express her weight in pounds.
4. American railways usually allow each passenger 150 pounds of baggage. Express this in kilograms.
5. A metric ton is 1000 kilograms. How many pounds is this in excess of the English ton?
6. It is sometimes said, "A pint is a pound, the world around." How many pounds does a pint of water weigh? (1 quart = 2 pints.)
7. An empty milk bottle is found to weigh 720 grams, and when it is filled with water, the bottle and water weigh 1670 grams: (*a*) how many cubic centimeters does it contain? (*b*) how many liters? (*c*) how many quarts?
8. A boy 5 feet 4 inches tall, and weighing 140 pounds, can run 100 yards in 11 seconds. Express these facts in metric units.
9. If sugar sells for 6 cents a pound, how much would 1 metric ton cost?
10. If the current price of platinum is $75.00 per ounce, what would be the price per gram?

12. Density. Everyone knows that lead is "heavier" than cork; and yet the question is sometimes asked, "Which is heavier, a pound of lead or two pounds of cork?" The word

"heavy" has two distinct meanings. Two pounds of cork are heavier than one pound of lead in the same sense that two pounds of coal are heavier than one pound of coal. In this case the word "heavy" refers to the total weight of the material. On the other hand, lead is "heavier" than cork in the sense that a piece of lead weighs more than an equal bulk of cork. The word "density" is used to designate more precisely this inherent property of the lead and the cork. That is, lead has a greater density than cork.

The density of a substance is its weight per unit volume. Thus the density of water is about 62.4 pounds per cubic foot, or 8.34 pounds per gallon. The density of copper is 555 pounds per cubic foot, or 0.321 pounds per cubic inch. In scientific work it is usual to specify the density of a substance in grams per cubic centimeter (g/cm^3).

TABLE OF DENSITIES *

(In grams per cubic centimeter)

Platinum	21.5	Hard woods (seasoned)	0.7–1.1
Gold	19.3	Soft woods (seasoned)	0.4–0.7
Mercury	13.6	Ice	0.911
Lead	11.4	Human body	0.9–1.1
Silver	10.5	Cork	0.25
Copper	8.93	Sulfuric acid (conc.)	1.84
Brass	8.4	Sea water	1.03
Iron	7.1–7.9	Milk	1.03
Zinc	7.1	Fresh water	1.00
Glass	2.4–4.5	Kerosene	0.80
Granite, marble, etc.	2.5–3.0	Gasoline	0.75
Aluminum	2.65	Air	about 0.0012

13. Measurement of density. The simplest way to determine the density of a substance is to weigh the substance and measure its volume.

FOR EXAMPLE, a piece of pine 6 feet long, 1 foot wide, and 6 inches thick has a volume of 3 cubic feet. If it weighs 90 pounds, its density is 30 pounds per cubic foot.

* This table is for reference and is not to be memorized.

An empty kerosene can weighs 1.25 pounds, and when filled with kerosene, it weighs 36.25 pounds, so that the net weight of the kerosene in the can is 35 pounds. If the can holds 5 gallons, the density of the kerosene is 7 pounds per gallon.

A block of steel is 15 centimeters long, 6 centimeters wide, and 1.5 centimeters thick and weighs 1050 grams; then the density is $\frac{1050}{150}$, or 7.8 grams per cubic centimeter.

To find the density of an irregular piece of stone, we may determine its volume by the displacement of water. Suppose we have 100 cubic centimeters of water in a graduated cylinder, and when the stone is put in, the water level rises to 160 cubic centimeters (Fig. 9). Then the volume is 60 cubic centimeters. If the stone weighs 150 grams, its density is $\frac{150}{60}$, or 2.5 grams per cubic centimeter.

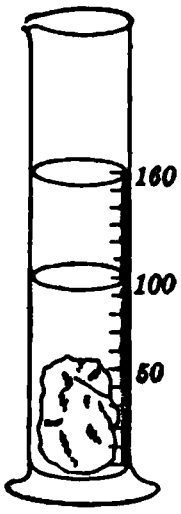

Fig. 9. Graduated cylinder used to find volume of stone.

From the preceding examples it will be seen that the density of a body is found by dividing its weight by its volume. Thus,

$$\text{Density} = \frac{\text{weight}}{\text{volume}}.$$

It is also evident that if we know the density of a substance, we can compute the weight of any volume of the substance. By this method engineers calculate the weight of buildings and bridges which it would be impossible to weigh. For,

$$\text{Weight} = \text{density} \times \text{volume}.$$

FOR EXAMPLE, an engineer finds by computation that a reënforced concrete pier contains 2500 cubic feet of material, and he knows that such material averages 150 pounds per cubic foot. Then the weight of the pier is equal to 2500 times 150, or 375,000 pounds (about 188 tons).

If it is the volume of a thing that we want to know, we have

$$\text{Volume} = \frac{\text{weight}}{\text{density}}.$$

FOR EXAMPLE, the volume of a 100-gram brass weight is $\frac{100}{8.4}$, or 11.9 cubic centimeters.

Problems

(Use data given in table on page 10 when necessary.)

1. A block of iron is 10 centimeters by 8 centimeters by 5 centimeters, and weighs 3 kilograms. What is its density expressed in grams per cubic centimeter?

2. A block of stone measures 4 feet by 2 feet by 15 inches, and weighs 1625 pounds. Find its density in pounds per cubic foot.

3. A flask with a capacity of 120 cubic centimeters is filled with mercury. How many kilograms of mercury does it hold?

4. An aluminum cylinder is 8 centimeters long and 4 centimeters in diameter. How many grams does it weigh?

5. What is the weight of a granite sphere 6 feet in diameter? Assume the density of granite to be 170 pounds per cubic foot. Volume of a sphere $= \frac{1}{6}\pi D^3$.

6. Given the density of water in the English system as 62.4 pounds per cubic foot, and a table of densities in the metric system, how would you compute the corresponding densities in the English system?

7. How many pounds does 1 cubic foot of aluminum weigh?

8. The cork in a life preserver weighs 20 pounds. What is its volume in cubic feet?

9. A cake of ice measures 18 inches by 12 inches by 10 inches. How many pounds does it weigh?

10. A cylindrical railway water tank measures on the inside 10 feet in depth and 6 feet in diameter. How many tons of water does it hold?

11. A quart bottle is weighed empty and then full of milk. How many pounds should it gain in weight?

12. A silver ball, apparently solid, is in reality hollow. It weighs 4.5 kilograms and is 10 centimeters in diameter. What is the volume of the cavity?

13. A metal tube weighs 10.1 kilograms. It is 10 centimeters long, its outside diameter is 13 centimeters, and its inside diameter is 5 centimeters. Find (*a*) the density of the metal and (*b*) what the metal probably is.

14. How many cubic centimeters of concentrated sulfuric acid must be added to 1 liter of water in order that the diluted acid may have a density of 1.3 grams per cubic centimeter?

15. Calculate the volume in cubic feet of your own body.

14. Units of time. The second, the minute, and the hour are used by all civilized nations as units of time. An hour is one twenty-fourth of the time from noon to noon. A minute is a sixtieth of an hour; and a second is a sixtieth of a minute. Thus an hour contains 60 times 60, or 3600 seconds, and a mean solar day contains 24×3600, or 86,400 seconds.

Ordinary time intervals are measured with clocks or watches. For short intervals a special type of watch is used, known as a **stop watch** (Fig. 10); it can be read to a fifth of a second.

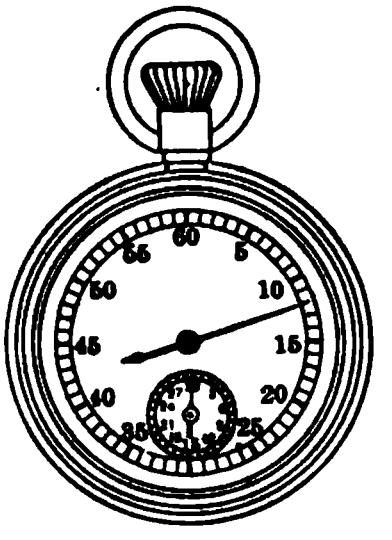

Fig. 10. A stop watch which measures time to one fifth of a second.

SUMMARY OF PRINCIPLES IN CHAPTER I

Density is weight of unit volume.

$$\text{Density} = \frac{\text{weight}}{\text{volume}}.$$

$$\text{Weight} = \text{density} \times \text{volume}.$$

$$\text{Volume} = \frac{\text{weight}}{\text{density}}.$$

QUESTIONS*

1. What are the meanings of the prefixes kilo-, centi-, and milli-, used in the metric system?

2. What two uses has cork which depend on its small density; and what three uses has lead due to its great density?

3. How would you measure the diameter of a small steel ball?

4. How can the thickness of this page be measured?

* In trying to find the answers to these questions, the student is expected to consult various reference books, such as dictionaries, encyclopedias, engineering handbooks, and popular-science magazines. He is also expected to keep his eyes open outside of the classroom, and to ask questions of artisans and business men.

5. What is the difference between a ship's chronometer and an alarm clock?

6. How could you determine the inside diameter of a glass tube which has a fine bore?

7. Read in an encyclopedia the history of our English standards of length.

8. Learn from an encyclopedia about the origin of the metric system. When was it officially introduced into the United States?

9. What advantages has the metric system over the English system of measures?

10. Why is it that the United States and Great Britain are the only two civilized countries that do not use the metric system commercially?

Practical Exercises

1. Standard time. How does your local jeweler get "standard time," by which to set his clocks and watches correctly?

2. Errors of measures. How would you test the accuracy of a quart measure? Bring one from home and try it.

3. Household measurements. What units of measurement are used in your home? Make a list of all units found, and show how they are related. (Consult *Measurements for the Household.* — U. S. Bureau of Standards Circular No. 55.)

4. Accuracy of a storekeeper. How nearly right must a quart measure be to be legally permissible for a storekeeper to use in your state? How nearly right must a storekeeper's scales be to be legally permissible? (Hint. Make an excursion to your City Sealer's office.)

5. Accuracy of a carpenter. When a house is built, what errors in distances are considered allowable in setting up the frame as compared with what the plans call for?

6. Accuracy of a machinist. Automobile cylinders often wear more on one side than on another so that they become oval instead of round. When testing for this, how closely does an automobile repair man measure various diameters of a cylinder?

CHAPTER II

SIMPLE MACHINES

Levers of various kinds — principle of moments — force at the fulcrum — center of gravity in general — weight of a lever — stability — mechanical advantage — wheel and axle — pulley systems — parallel forces.

Work — principle of work — differential pulley — inclined plane — wedges and cams — screws — gears — combinations of simple machines — power — transmission of power.

Friction — traction — factors affecting friction — lubrication — coefficient of friction — efficiency of machines.

15. Why we use machines. With a rope and tackle a man can lift a piano up to a window on the second floor. With a skid a boy can roll a barrel of flour up into a truck. With a claw hammer a girl can pull a nail out of a box, although she could not move the nail at all with her fingers alone. It is obvious that we can do many things with the aid of simple machines that otherwise would be quite impossible because we are not strong enough. In other words, machines enable us to *multiply the force*, that is, the push or pull, which we can exert. Furthermore, some machines help us to do things more quickly or more conveniently than we could without them. For example, with a fishing rod we can place the bait to better advantage and can haul in the fish much faster. Most important of all, we often employ machines in order to make use of forces exerted by animals, wind, water, or steam.

In this chapter we shall learn that all complex machines are built out of simpler parts — levers, wheels, cranks, gears, pulleys, etc. We shall learn to compute how much advantage we gain by the use of various complex machines and how to use them more efficiently.

16. A lever with two equal weights. Doubtless the simplest machine is a lever, such as a seesaw or the scale beam of a platform balance or the walking beam of a steamboat. In the case of the balance (Fig. 11), the beam swings freely under the influence of the equal weights W_1 and W_2 only when the distance AF equals the distance BF. In general, *equal weights will balance only when placed at equal distances from the point of support.* In the technical language of physics, this point F about which the rigid bar turns is called the **fulcrum.** The fulcrum in a beam balance consists of a sharp hard support called a knife-edge, and each end of the beam carries a pan which is suspended from a knife-edge. These precautions are taken to minimize friction.

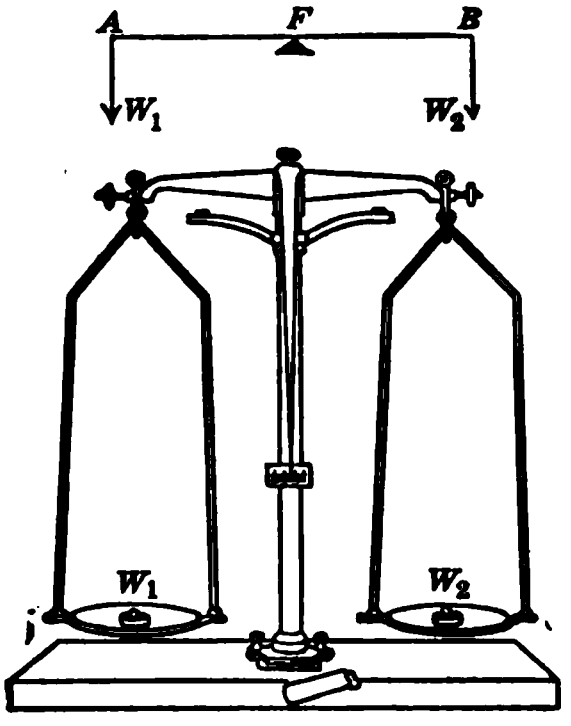

Fig. 11. A lever with equal arms and equal weights.

17. A lever with two unequal weights. Very often the weights or forces applied to a lever are not equal; as, for example, when two persons of unequal weight are seesawing, or in the case of an ordinary pump handle. It is evident that at equal distances the larger weight would have the greater tendency to tip the lever. It is also evident that with equal weights at unequal distances the weight at the greater distance from the fulcrum has the greater tendency to tip the lever. Therefore in order to have two unequal weights balance, they must be so placed that the smaller weight is at the greater distance from the fulcrum.

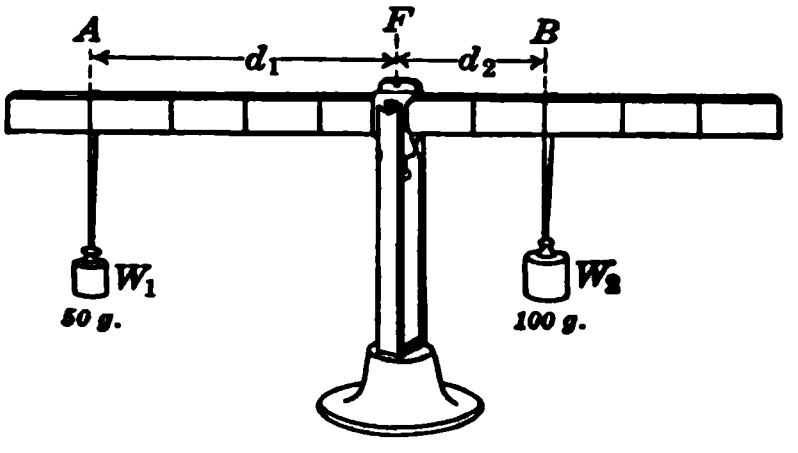

Fig. 12. A lever with two unequal weights.

If we balance an ordinary meter stick in the middle (Fig. 12) and suspend a 50-gram weight W_1 at A, which is 40 centimeters from the fulcrum F, and then hang a 100-gram weight W_2 on the other side at such a point as just to balance the first weight, we shall find that the point B, where the 100-gram weight is hung, is about 20 centimeters from F, or half as far from the fulcrum as the 50-gram weight.

Careful experiments show that any two unequal forces will balance only if *the force on one side multiplied by its perpendicular distance from the fulcrum equals the force on the other side multiplied by its distance from the fulcrum.* Thus, in figure 12,

$$W_1 \times d_1 = W_2 \times d_2.$$

This relation of the forces and distances may also be expressed by the equation

$$\frac{W_1}{W_2} = \frac{d_2}{d_1}$$

which may be stated in words as follows: *the forces are inversely proportional to their distances from the fulcrum.* This means that if one force is *three* times as great as another, then it must be *one third* as far away from the fulcrum as the other in order to make the lever balance.

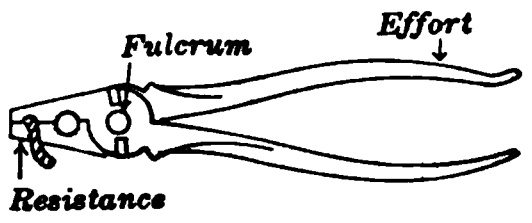

Fig. 13. Pliers are levers with rivet as fulcrum.

Crowbars, shears, glove stretchers, pliers (Fig. 13), etc., are all examples of this sort of lever.

18. A lever with the fulcrum at one end. When a wheelbarrow is used to carry a heavy weight (Fig. 14), we have a lever with the fulcrum F located at one end. The same principle is involved as in the levers just discussed. There are two tendencies at work which must balance; namely, the tendency of the weight W to tip the lever down and the tendency of the effort E or pull

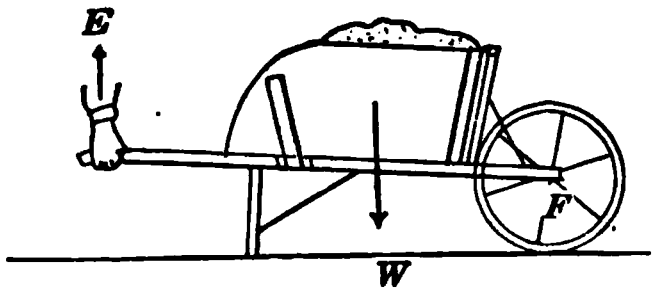

Fig. 14. A wheelbarrow is a lever with the fulcrum at the axle of the wheel.

applied to lift it up. The weight multiplied by the perpendicular distance from the fulcrum to its line of action measures its turning effect about the fulcrum; that is, its tendency to tip the lever down. This must be balanced by an equal turning effect in the opposite direction, namely, the effort or upward pull multiplied by its distance from the fulcrum.

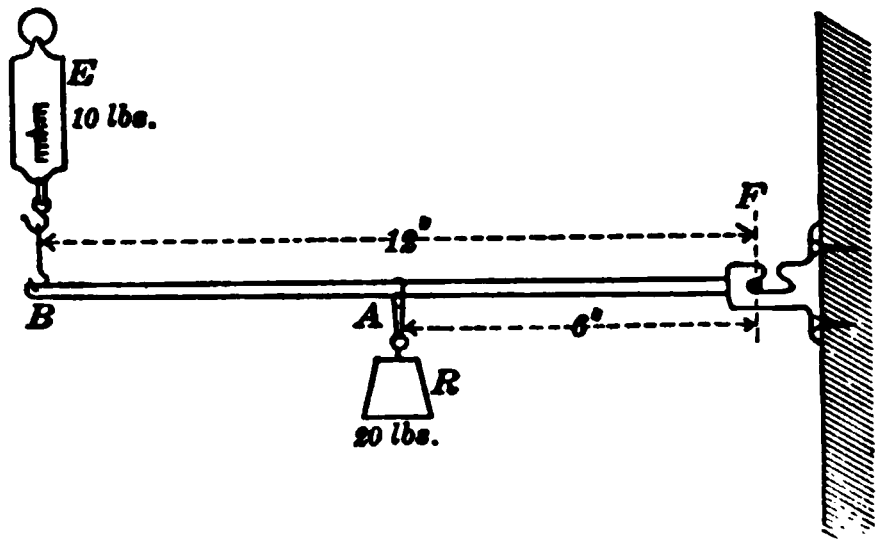

Fig. 15. A lever with fulcrum *F* at one end.

Suppose we fasten a light stick (Fig. 15) by an axle *F* to an upright support so that the stick is free to turn, and hang a weight *R*, say 20 pounds, at a distance of 6 inches from the fulcrum *F*. Then if we pull up with a spring balance at a point *B*, 12 inches from the fulcrum *F*, we find that the effort or pull *E*, measured by the spring balance, is about 10 pounds. (Of course allowance has to be made for the weight of the stick.)

The equation representing these tendencies to turn the stick in opposite directions would be as before

$$R \times AF = E \times BF.$$

A nutcracker and a crowbar when used with one end on the ground (Fig. 16) are examples of levers with the fulcrum at one end.

Sometimes, as in the case of the forearm when the hand supports a weight, the fulcrum is at one end of the lever, the weight or resistance to be overcome is at the other end, and the effort is applied at some

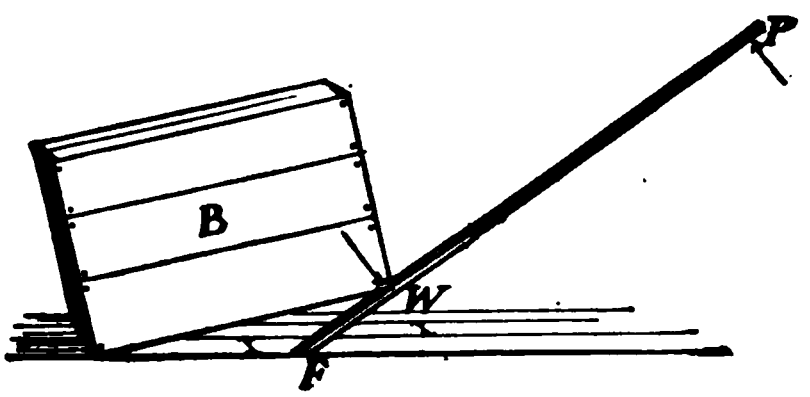

Fig. 16. A crowbar used with the ground as fulcrum.

point in between. This is further illustrated in figure 17 where a man is shown holding a weight *R* on a shovel, with his left hand *F* acting as the fulcrum, while he applies an upward force *E* with his right hand.

Fig. 17. The shovel is a lever with weight near one end; hand at other end acts as fulcrum.

We may illustrate this case by the same apparatus (Fig. 18) which we have just used. In this experiment we place the 10-pound weight *R* 12 inches from the fulcrum *F* and attach the spring balance *E* at a point 6 inches from the fulcrum. We find that the pull needed is now 20 pounds, or just double the weight. In this case the weight-distance is double the effort-distance, and the effort is double the weight.

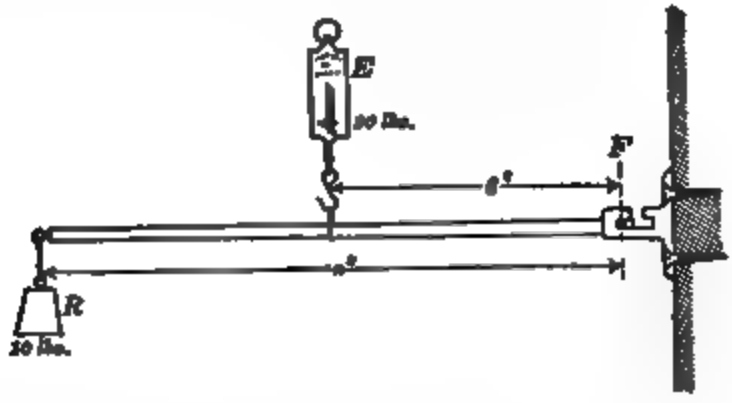

Fig. 18. A lever with weight at one end and fulcrum at the other end.

Thus we see that the same principle holds wherever the resistance (weight) and the effort (upward pull) are applied. This may be stated as follows:

Resistance × its distance from fulcrum
= effort × its distance from fulcrum.

19. Lever with two weights. It often happens that a wheelbarrow is used to carry two weights, such as two bags of cement or a box and a keg, as shown in figure 19. To get the upward pull we have merely to compute the turning effect of each of the weights W_1 and W_2 about the fulcrum F and make the sum of these effects equal to the turning effect of the upward pull or effort E. That is,

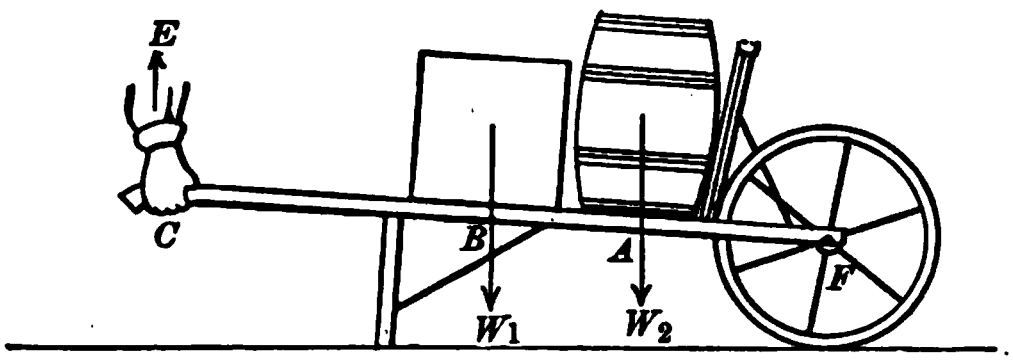

Fig. 19. Wheelbarrow with two weights.

$$W_1 \times BF + W_2 \times AF = E \times CF.$$

The distances CF, BF, and AF should be measured perpendicularly to the lines of action of the forces.

In general, then, we see that we can balance the turning effect of two or more weights by multiplying each weight by the perpendicular distance of its line of action from the fulcrum, and making the sum of these products equal to the product of the effort by the perpendicular distance of its line of action from the fulcrum.

20. Principle of moments. It has been seen that the turning effect of a force depends on two factors, the amount of the *force* and the *distance* of its line of action from the fulcrum. This product — **force times its perpendicular distance from the fulcrum** — is called the **moment** of the force.

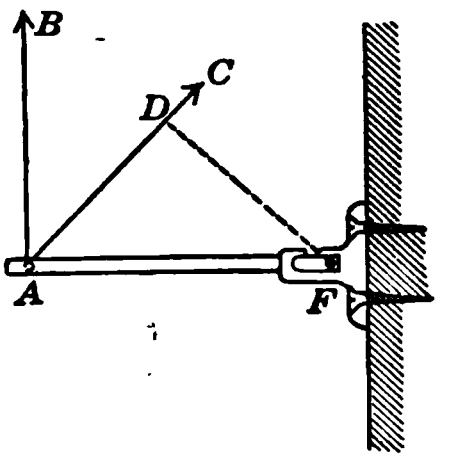

Fig. 20. Moment of a force equals force times its perpendicular distance from fulcrum.

For example, let AF (Fig. 20) be a rigid bar which can rotate about F. The moment of the force B applied at A is equal to B times FA; and the moment of force C is equal to C times FD. If B equals C, which is the greater moment?

In general, for a lever to be in equilibrium, *the sum of the moments of the forces tending to turn it in one direction must equal the sum of the moments of the forces tending to turn it in the opposite direction.*

QUESTION

A mechanic finds difficulty in turning an inch-pipe with a 6-inch Stillson wrench but finds it easy to turn the pipe with an 18-inch wrench. Explain.

21. Force at the fulcrum. In the case of the man with the shovel (Fig. 17), we have called his left hand the fulcrum. But it is quite as evident that this hand must exert a force (in this case a downward push) as that the other hand must pull up. Indeed, we might have thought of the right hand as the fulcrum of a lever with unequal arms and the left hand as exerting the effort.

In general, when three forces act on any object, the point of application of any one of the three forces can be thought of as the fulcrum, and the other two forces as resistance and effort respectively.

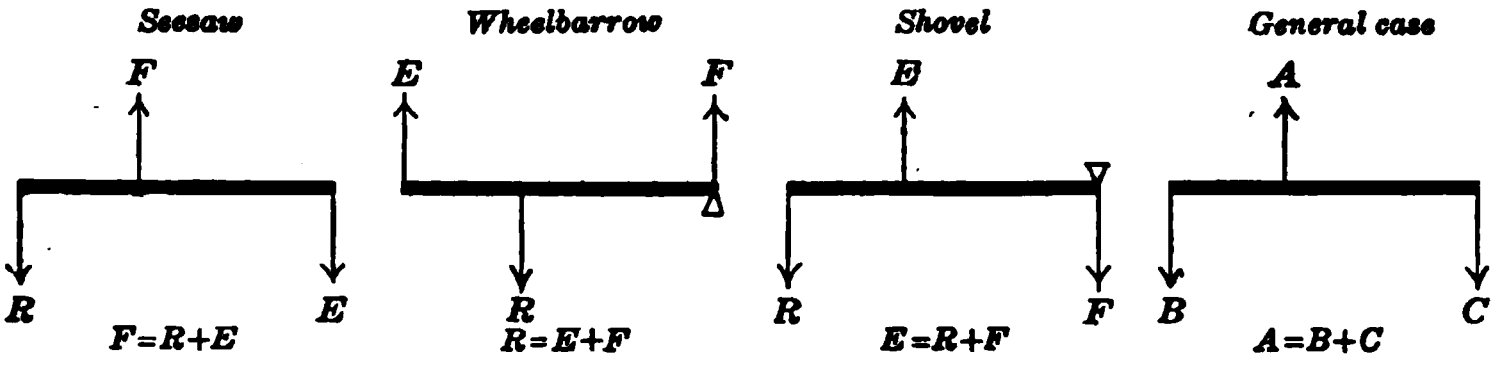

Fig. 21. Force exerted at the fulcrum of a lever.

To find how much force the fulcrum exerts in any of the cases so far discussed, we may draw diagrams like those in figure 21. In the first diagram the fulcrum is between the weights or forces, as in the case of a seesaw; in the next diagram the fulcrum is at one end and the effort at the other, as in the case of a wheelbarrow; in the third diagram the fulcrum and resistance are at the ends, as in the case of a shovel. In all cases the principle is exactly the same (see general case).

When there are three (or more) parallel forces in equilibrium, the sum of the forces pulling one way must equal the sum of the forces pulling the other way. By applying this principle in any particular case, we get an equation, like one of those in figure 21, which can be solved for F, the force exerted by the fulcrum.

Questions and Problems

(Make diagrams to illustrate the following problems.)

1. Draw an outline sketch and indicate the fulcrum and the direction of the two forces in the case of a pair of shears, a glove stretcher, a can opener, a pair of tongs, and a nutcracker, regarded as examples of the lever.

2. What weight placed 20 inches from the fulcrum will balance 100 pounds placed 8 inches away on the opposite side? What is the force exerted at the fulcrum?

3. A piece of wire which is to be cut with shears is placed 0.5 inches from the rivet. If a force of 25 pounds is applied on the handles 6 inches from the rivet, how much force is exerted on the wire?

4. Why are the shears used for cutting paper made with long blades and short handles, while those used to cut metal are just the opposite?

5. A plank 12 feet long is to be used as a seesaw by two boys who weigh 100 pounds and 140 pounds. How far from the lighter boy must the prop be placed? (Let x = distance from small boy and $12 - x$ = distance from big boy. Neglect weight of plank.)

6. The handles of a wheelbarrow (Fig. 14) are 4 feet 6 inches from the axle, and the load of 200 pounds can be considered as 18 inches from the axle. How much effort must be exerted to raise the handles?

7. Why is it easier to lift the handles of a wheelbarrow if the load is placed as near the wheel as possible?

8. In lifting a shovel full of coal do you lift up with one hand as hard as you push down with the other? Explain.

9. When a load is carried on a stick over the shoulder, why should the load be carried near the shoulder rather than far out on the stick?

10. A crowbar 5 feet 6 inches long is used to lift a weight of 400 pounds. The fulcrum is placed 6 inches from the weight. Calculate the effort needed. (Two solutions are possible.)

11. What levers are there in the human body?

22. Center of gravity. So far in our study of levers we have assumed that the weight of the lever itself could be neglected, but in practice this is not always the case. It is our problem now to find how to make allowance for the weight of the lever.

We have already seen that a lever carrying two weights (Fig. 22) can be supported at a point in between, which we have called the fulcrum, but which we may now call the "center of gravity" or "center of weight." The force necessary to support this point is the same as it would be if the whole weight were concentrated there. In the same way we could support a bar carrying three or more weights on a single fulcrum, if it is placed at the right point. That point would be the **center of gravity** of the weights. In general, *the center of gravity of a body is the point at which we can consider its whole weight concentrated.* To find the position of the center of gravity, we have simply to find the point at which the object would balance on a knife-edge. This may be computed, but it is usually easier to locate it experimentally.

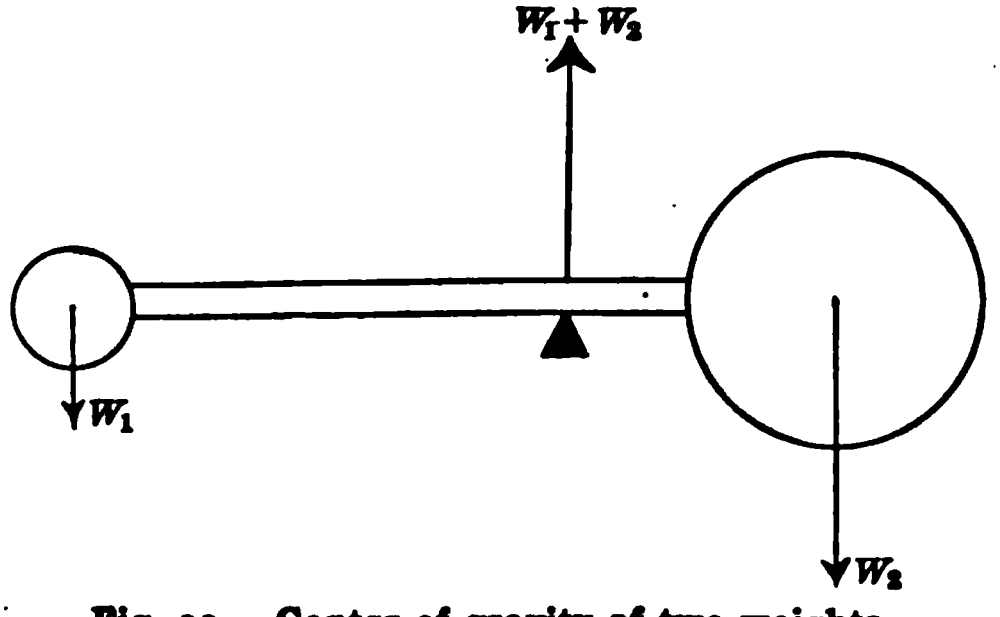

Fig. 22. Center of gravity of two weights.

23. How to find a center of gravity by experiment. If the shape of the object is simple and its density is everywhere the same, as in the case of a shaft or a board, we should expect the center of gravity to be in the middle, and if we try to balance the object on some sharp edge, we find that the center of gravity is indeed located at the geometrical center. In the case of an irregularly shaped object like a baseball bat, the simplest way is to balance the bat on a knife-edge. In the case of a chair, the center of gravity may be found by considering that, if

the chair is hung so as to swing freely, the center of gravity will lie directly under the point of suspension. Therefore, if a chair or any other irregular object is hung from two points successively, the point of intersection of the plumb lines from these points will locate the center of gravity.

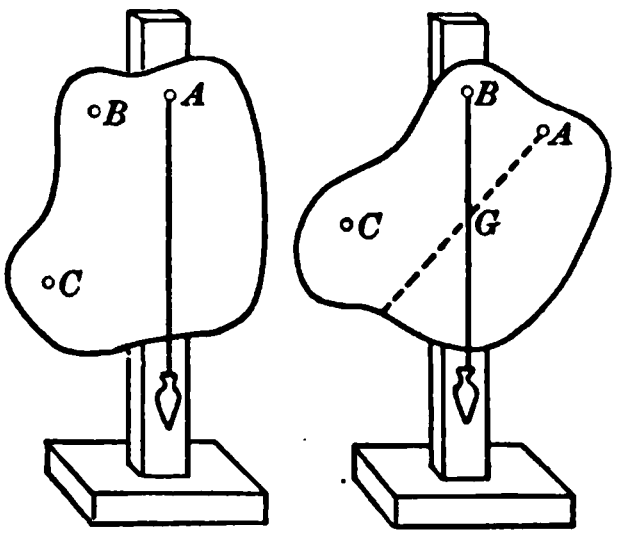

Fig. 23. Finding the center of gravity with a plumb line.

To make this clear, let us take an irregular sheet of zinc and drill three holes near the edge, *A*, *B*, and *C* in figure 23. Let the zinc be hung from a pin put through the hole *A*, and let a plumb line also be hung from the pin. Draw a line on the zinc to show where the plumb line crosses it. Then let the zinc be hung from another hole *B* and draw another line in a similar way. The point of intersection *G* is the center of gravity. When the zinc is hung from the third hole *C*, the plumb line will pass through the center of gravity already found.

In the case of a ring, or a cup, or a boat, the center of gravity will not lie in the substance itself, but in the empty space inside; but this will not bother us in answering questions about how such objects act. We may, if we like, think of such a center of gravity as rigidly attached to the object by a very light, stiff framework.

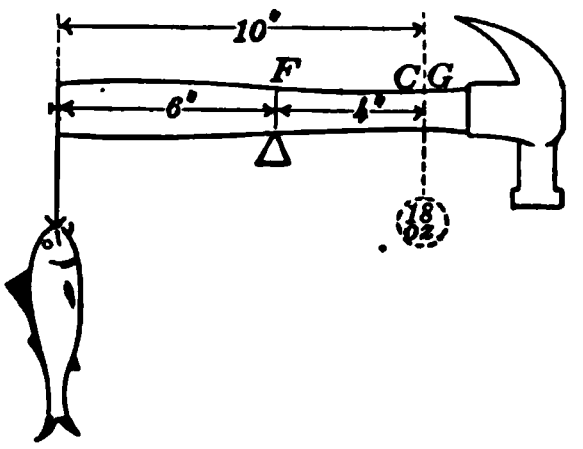

Fig. 24. Balancing a fish against the weight of a hammer.

We shall find this idea of the **center of gravity** especially convenient in problems where the weight of a lever has to be considered, for we can now assume that the *whole weight of the lever is concentrated and acting at its center of gravity.*

FOR EXAMPLE, suppose an 18-ounce hammer balances 10 inches from the handle end. When a fish is tied to the end of the handle, the whole balances 6 inches from the end. How much does the fish weigh?

Let us first draw a careful diagram (Fig. 24). We may consider the weight of the hammer, 18 ounces, as concentrated at a point *CG*, 10 inches from the end of the handle or 4 inches from the fulcrum. Let x be the weight of the fish, which is applied 6 inches from the fulcrum. Then we have

$$6x = 4 \times 18$$
$$x = 12 \text{ ounces, the weight of the fish.}$$

24. Stability. The conception of center of gravity also helps us to understand another kind of problem.

If we place a block *A* on an inclined plane and drop a plumb line from its center of gravity, the line falls within the base of the block (Fig. 25). If we place on the same inclined plane another block *B* which has the same base but twice the height of *A*, a plumb line from its center of gravity will fall outside the base and the block *B* will tip over.

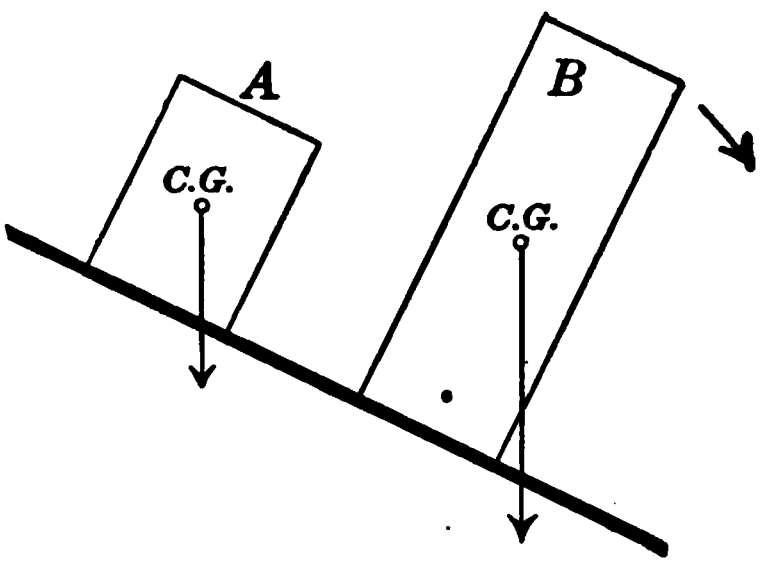

Fig. 25. Stable and unstable objects.

In general, an object will be stable, that is, it will not tip over of itself, if a plumb line from its center of gravity falls within its base. This is called the **condition of stability.** Some objects are, however, easier to knock over than others, even though they will not tip over of themselves. Evidently the stability of an object in this sense is greater, *the greater its weight, the larger its base,* and *the lower its center of gravity.*

Questions and Problems

1. A uniform bar 10 feet long has a load of 45 pounds suspended from one end and balances when a support is placed 2 feet from that end. What is the weight of the bar? (The center of gravity of the bar is in the middle.)

2. The standard length of a railroad rail is 33 feet, and a size commonly used weighs 80 pounds per yard. If four men take hold of one end of such a rail lying on the ground, how much must each man lift in order to raise the end from the ground?

3. A boy has a 2-pound fishing rod 10 feet long, the center of gravity of which is 3.5 feet from the thick end. He finds the weight of his string of fish by hanging them from the thick end of the rod and then balancing the rod on a fence rail. He notes that it balances at a point 15 inches from the end. How many pounds of fish has he?

4. A pole 20 feet long weighs 120 pounds. When a 30-pound bag of meal is hung at one end, the balancing point is 3 feet from the same end. Where is the center of gravity of the pole?

5. A 6-foot crowbar balances at a point 2.5 feet from its sharp end. If a weight of 30 pounds is hung 0.5 feet from this end, and 50 pounds is hung 1 foot from the other end, it balances at its mid-point. How heavy is the bar?

6. A uniform beam AB, 20 feet long, weighing 600 pounds, is supported by props placed under its ends. Four feet from prop A a weight of 200 pounds is suspended. Find the pressure on each prop. (Regard as a lever with its fulcrum at one end.)

7. A man and a small boy are carrying a basket containing a load of 100 pounds by means of a uniform rod 10 feet long. If the weight of the rod is 20 pounds, where must the basket be placed so that the man's load will be three times that of the boy's?

Fig. 26. Leaning Tower of Pisa, Italy.

8. Explain why the Leaning Tower of Pisa (Fig. 26) does not fall.

9. What means have been employed to increase the stability of automobiles?

10. Explain why a cart loaded with hay is more likely to overturn on a sidehill than the same cart loaded with sand.

11. Explain how a tip-cart loaded with bricks is dumped by lifting up the front edge of the body a few inches as shown in figure 27.

12. Compare the stability of human beings with that of four-footed animals.

13. Why does a man carrying a trunk upstairs on his back bend forward?

Fig. 27. Shifting the center of gravity of the load by tilting the cart body.

14. Illustrate with sketches the various methods employed to give the proper stability to objects in everyday use, such as lamps, clocks, chairs, pitchers, vases, etc.

25. Mechanical advantage. We have already seen that a man with a lever may lift a weight of 500 pounds by exerting a force of 100 pounds. In this case the resistance that can be overcome is 5 times the effort. For any machine *the ratio of the resistance to the effort is called the* ***mechanical advantage.***

But we have also seen that the resistance is to the effort *inversely* as the relative distances of the resistance and effort from the fulcrum. Often it is more convenient to *compute the mechanical advantage of a lever by dividing the lever arm of the effort by the lever arm of the resistance.* These statements can be briefly expressed in the equation:

$$\text{Mech. adv.} = \frac{\text{resistance}}{\text{effort}} = \frac{\text{effort arm}}{\text{resistance arm}}.$$

FOR EXAMPLE, the arms of the handle of an ordinary lift pump are 5 inches and 28 inches. Then the mechanical advantage of the pump handle is $\frac{28}{5}$, or 5.6. This means that 1 pound effort exerted on the handle gives 5.6 pounds pull on the pump rod.

26. Bent lever. In working with actual levers as we see them in practical machines we often find that the lever itself is not a straight bar, but is bent so that the two arms do not form a straight line.

FOR EXAMPLE, let us consider the case of an ordinary claw hammer as used to pull out a nail (Fig. 28). If we exert at B a pull or effort E of 60 pounds, what is the resistance R which the nail offers? We must first measure the effort-arm FB, which is found to be 12 inches, and then the resistance-arm FA, which is 1.5 inches. Then the moment of the effort is $E \times FB$ and the moment of the resistance is $R \times FA$. Making these two moments equal, we have

$$60 \times 12 = R \times 1.5$$

and $$R = 480 \text{ pounds.}$$

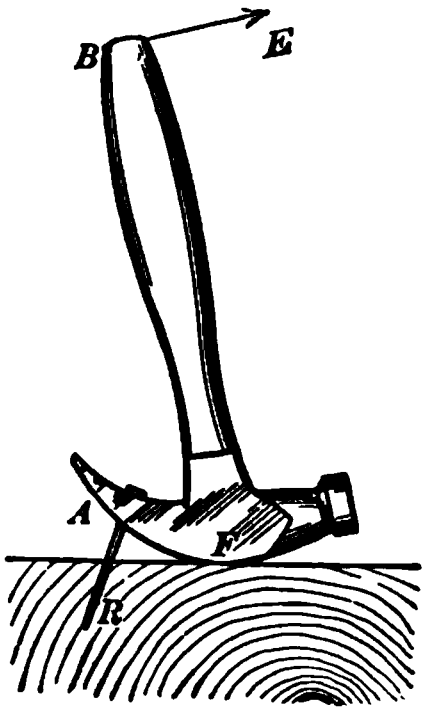

Fig. 28. Claw hammer acts as bent lever.

In this case it will be seen that the two arms of the lever are inclined to each other, but the principle of moments applies just as it would if it were a straight lever. We shall find many examples of bent levers as parts of machines, such as the lever used in operating the brake of an automobile, or the "bell-crank" lever used to transmit a pull around a corner in a railroad signal system. We may also regard many other objects, such as a door or gate, as bent levers.

Fig. 29. A gate regarded as a bent lever.

FOR EXAMPLE, suppose a gate (Fig. 29) 3.5 feet high and 5 feet wide weighing 100 pounds swings on hinges placed 3 inches from the top and 3 inches from the bottom. (*a*) What is the vertical force exerted by each hinge? (*b*) How great is the horizontal *pull* exerted by the upper hinge? (*c*) How great is the horizontal *push* exerted by the lower hinge?

(*a*) We shall assume that the gate is properly hung and that the weight, 100 pounds, is equally divided between the two hinges; that is, each hinge supports 50 pounds. Therefore the vertical forces Y_1 and Y_2 are each equal to 50 pounds.

(*b*) Let us assume that the entire weight of the gate, 100 pounds, is acting at its center C, and let us compute the moments about the lower hinge B. The moment of this weight about B is 100 times 2.5 (the perpendicular distance from B to the line of action CW of the weight). The moment about the lower hinge B of the horizontal pull X_1 exerted by the upper hinge A is 3 times X_1. Making these two moments equal we have

$$3 \times X_1 = 2.5 \times 100$$

and

$$X_1 = 83.3 \text{ pounds.}$$

(*c*) In a similar way we may assume the upper hinge A to be a fulcrum, and may compute the *push* X_2 exerted by the lower hinge. Thus we have

$$3 \times X_2 = 2.5 \times 100$$

and

$$X_2 = 83.3 \text{ pounds.}$$

Notice that in paragraphs (*b*) and (*c*) we have not considered the vertical forces Y_1 and Y_2. Why is it not necessary to do so?

Questions and Problems

1. A trade catalogue advertises a certain "hammer with a mighty pull." It claims that a force of 50 pounds on the handle exerts a pull of 1100 pounds on a nail. If the handle is 12 inches long, what is the distance between the nail and the fulcrum? How does this distance change as the nail is pulled out? What effect does this change have on the pull exerted on the nail? Illustrate your answer by sketches.

2. A rectangular door 7 feet high and 4 feet wide has its center of gravity at its geometrical center. It is hung on hinges placed 1 foot from the top and bottom. The door weighs 60 pounds. (*a*) What is the vertical force exerted by each hinge? (*b*) What is the horizontal *pull* exerted by the upper hinge? (*c*) What is the horizontal *push* exerted by the lower hinge?

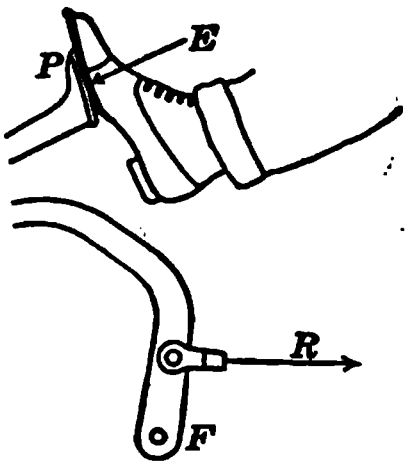

Fig. 30. Automobile foot brake is a bent lever.

3. Suppose the door in problem 2 were turned around so as to be 4 feet high and 7 feet wide, the hinges being placed 3 inches from the top and bottom respectively. (*a*) Will this change the vertical forces exerted by each hinge? (*b*) Will this change the horizontal forces? (*c*) In which case are the stronger hinges required?

4. The foot brake on a certain automobile has the shape shown in figure 30. It turns about a fixed point *F*, and when the foot presses on the pedal *P*, there is a much greater force exerted on the rod *R*. Indicate on a sketch just how you would compute the moment of the effort and the moment of the resistance. What is the mechanical advantage of the lever shown in figure 30? (Measure dimensions.)

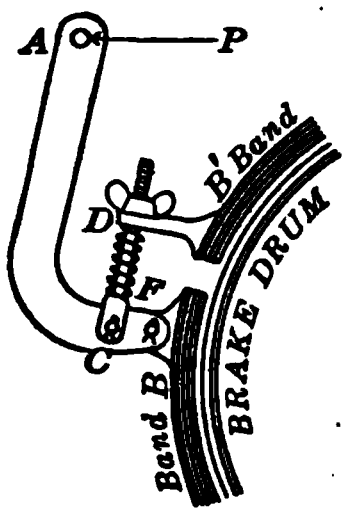

Fig. 31. A bent lever used to contract an automobile brake band.

5. On the same automobile the brake rod is attached to another bent lever (*AF* in figure 31) so that a push *P* exerted at *A* tends to contract the brake band *BB'* around the outside of a drum on the rear wheel. Show by a sketch how you would compute the contracting force (that is, the force which brings *B* and *B'* nearer together) if you knew the push at *A* and the dimensions of the lever.

Practical Exercise

Automobile brake levers. Investigate how the emergency or hand brake on some automobile works. Make a sketch showing the dimensions. Compute the mechanical advantage of each lever involved.

27. Wheel and axle. A special form of lever consists of a wheel or crank which is fastened rigidly to an axle or drum. The weight to be lifted, or the resisting force of whatever kind, is generally applied to the axle by means of a rope or chain, and the effort, or pull, is exerted on the rim of the wheel, as shown in figure 32. In calculating the effort E needed to balance a given resistance W, we have merely to take moments about the center F of the wheel and axle. If we call the radius of the wheel R and that of the axle r, then,

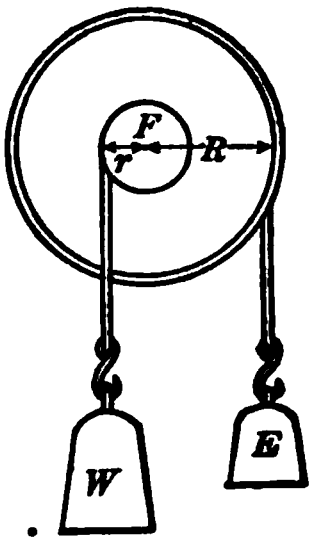

Fig. 32. Wheel and axle.

$$\text{Weight} \times \text{axle-radius} = \text{effort} \times \text{wheel-radius}$$

or $$W \times r = E \times R$$

or $$\frac{W}{E} = \frac{R}{r}.$$

In words this may be stated thus: *the weight lifted on the axle is as many times the force applied to the wheel as the radius of the wheel is times the radius of the axle.* Therefore the ***mechanical advantage*** *of the wheel and axle is equal to the radius of the wheel divided by the radius of the axle.*

It will be useful to remember that the diameters or circumferences of the wheel and axle bear the same ratio as their respective radii.

28. Uses of the wheel and axle. A **windlass** used in drawing water from a well by means of a rope and bucket is an application of the principle of the wheel and axle. In the windlass a crank takes the place of a wheel, and the length of the crank corresponds to the radius of the wheel.

For example, suppose we wish to lift a load of 75 pounds with a windlass (Fig. 33) whose drum is 6 inches in diameter and whose crank handle is 15 inches from the center of the drum. Since the radius of the axle is 3 inches, we have

$$15 \times E = 3 \times 75$$

and $$E = 15 \text{ pounds.}$$

Another application of the wheel and axle is the **capstan.** In this case, the axle or drum is vertical and the effort is sometimes applied by means of handspikes. On modern ships, steam or electric power is used to rotate the drum. The **steering wheel** on a boat, the **hand wheel** used on the brake of a freight or street car, and numerous devices about the house, such as the ice-cream freezer, bread mixer, wringer, and door knob, are also examples of the wheel and axle.

Fig. 33. Diagram of a windlass.

29. The pulley. The **fixed pulley,** shown in figure 34, consists of a wheel with a grooved rim, called a **sheave,** free to rotate on an axle which is supported in a fixed **block.** A flexible rope or cable passes over the wheel. It is evident that if equal weights or equal forces are applied to the ends of the rope, they just balance each other. That is, the effort E is equal to the load or resistance W, and therefore the mechanical advantage in the fixed pulley is 1. However, it is sometimes more convenient to exert a certain pull downwards rather than upwards.

Fig. 34. Fixed pulley.

Oftentimes the block is attached to the weight to be lifted,

as shown in figure 35, and then it is called a **movable pulley.** Here the effort E is not equal to the weight W, for it will be seen that the load W is supported by *two* ropes, and therefore each exerts an upward pull equal to *one half* the weight. That is,

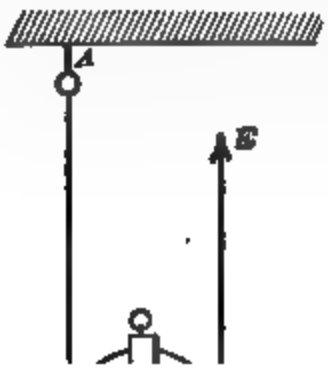

Fig. 35. Movable pulley.

$$E = \frac{W}{2} \text{ or } \frac{W}{E} = 2.$$

Therefore, the mechanical advantage of a single movable pulley is 2.

30. Combinations of pulleys. In practical work it is common to use *both* fixed and movable pulleys, such as a fixed block with two sheaves and a movable block with two sheaves, as shown in figure 36. One end of the rope is attached to the fixed block, and the effort is applied to the other end of the rope. Let us compute the relation between the weight to be lifted and the effort applied. From figure 36 it will be seen that the weight and the movable block are supported by *four* ropes, and so the pull on each rope, neglecting the weight of the block, is *one fourth* the weight W. It will also be seen that the pull E is equal to that in each of the ropes, since a fixed pulley changes only the direction of the pull. Therefore

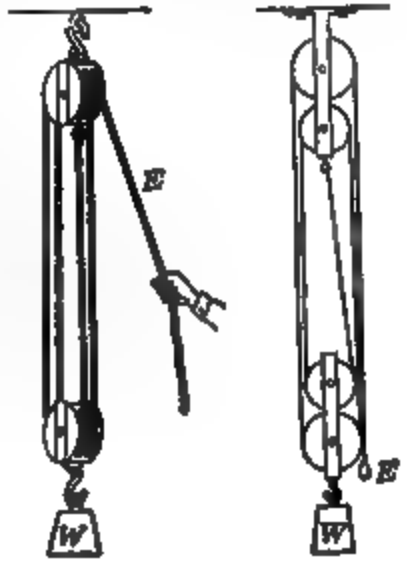

Fig. 36. Two double blocks.

$$E = \frac{W}{4}$$

and the mechanical advantage W/E is 4.

This means that, if friction and the weight of the movable

block are disregarded, a pull of 100 pounds applied at E would just balance a weight of 400 pounds at W.

In general, we can find the mechanical advantage of any pair of pulleys by counting the number of ropes acting on the movable block.

31. Parallel forces in general. In many of the machines so far studied, for example the wheelbarrow with one or two loads, the coal shovel, and sometimes the wheel and axle, all the forces acting are parallel to each other. In all these cases two general principles are involved, which sum up all that we have learned. A simple experiment will make these principles clear.

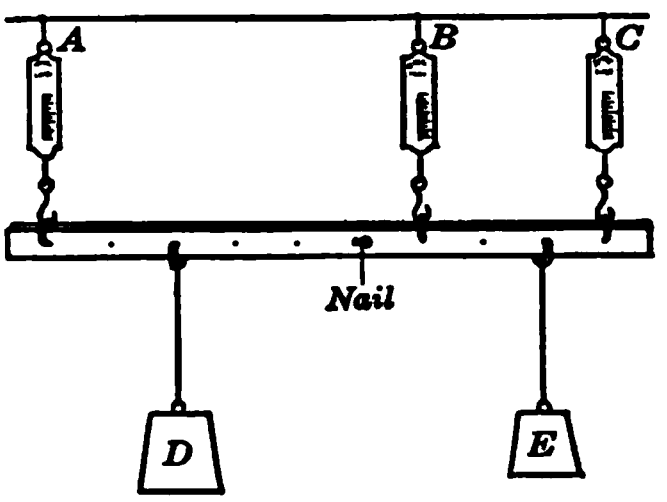

Fig. 37. Parallel forces.

Hang a light stick (Fig. 37) by two or more stirrups attached to spring balances A, B, C, and let several weights D, E be hung from it at various points. By reading the balances it will be easy to check up the fact that *the sum of the forces pulling up is equal to the sum of the forces pulling down.* Even without doing the experiment we could have foreseen that this must be true, because if either set of forces overbalanced the other, the stick would move.

Now suppose that there happen to be several holes through the stick and that a nail is carefully driven through one of them into the wall behind. Then think of the nail as the fulcrum of a lever, and compute the moments of all the forces tending to turn the stick clockwise about the nail and the moments of those tending to turn it counterclockwise. It will be found that *these two sets of moments just equal each other.* Here also we could have foreseen that this must be true, because if either set of moments overbalanced the other, the stick would begin to turn around the nail.

Evidently the nail could have been put through a hole at *any* point along the stick. So the moments calculated around *any* point must balance.

This experiment shows that when several parallel forces are in equilibrium, two conditions must be fulfilled:

(1) *The sum of the forces pulling in one direction must equal the sum of the forces pulling in the opposite direction.*

(2) *The sum of the moments tending to rotate the body in one direction around any point whatever must equal the sum of the moments tending to rotate the body in the opposite direction around the same point.*

These two statements are so important that they may well be memorized.

FOR EXAMPLE, suppose that a 3000-pound automobile is standing on a bridge one fourth of the way across (Fig. 38) and that we wish to know how much of its weight A is carried by each of the supports at the ends of the bridge. Let B and C be the two upward forces the magnitudes of which are to be found. Suppose we use principle (2) above, and take moments around the left-hand end of the bridge, where C acts. Then C has no moment and we have

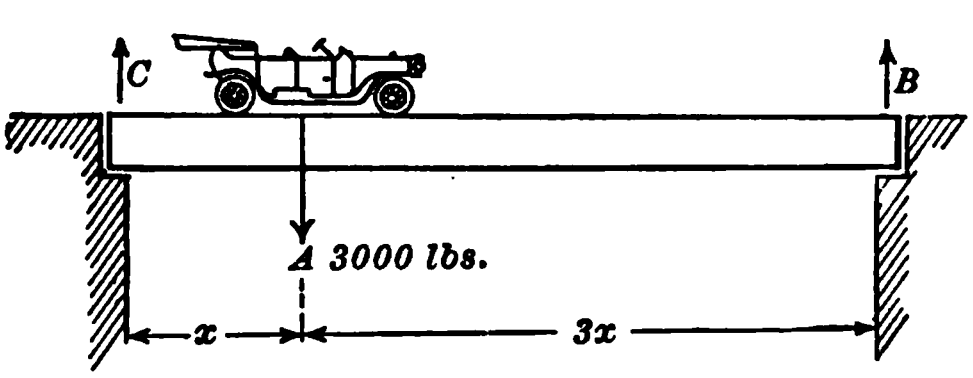

Fig. 38. Bridge with automobile on it.

$$B \times 4x = 3000 \times x$$
$$B = 750 \text{ pounds.}$$

Next, using principle (2) again, take moments around the right-hand end, where B acts. We have

$$C \times 4x = 3000 \times 3x$$
$$C = 2250 \text{ pounds.}$$

Finally, we use principle (1) above as a check on the correctness of our numerical work. We should have

$$B + C \text{ (upward)} = A \text{ (downward)},$$

which checks because $750 + 2250 = 3000$.

PROBLEMS

(It will greatly assist in the solution of these problems to draw a careful diagram in each case.)

1. The diameter of an axle is 1 foot, and the diameter of the circle in which a crank on the axle moves is 3 feet. If 150 pounds is the weight to be raised, how much force must be applied to the crank?

2. The crank on a grindstone is 9 inches long, and the diameter of the stone is 30 inches. If 50 pounds is the force applied on the crank, what force can be exerted on the rim of the stone?

3. What must be the ratio of the diameters of a wheel and axle in order that an effort of 150 pounds may support a load of 1 ton? What is the mechanical advantage?

4. Two single fixed pulleys are used to raise a barrel of flour, as shown in figure 39. If the barrel of [illegible] pounds, how much does the horse hav

5. The sail of a boat is to be rais movable single block attached to th double block attached to the top of of the rope being tied to the movable b resistance can be overcome by 100 p the rope?

6. A pair of triple blocks (three block) is used to raise a 1-ton weight. The rope is attached to the upper fixed block. What effort must be applied? Disregard friction.

Fig. 39. Simple pulley system.

7. An automobile gets stuck in the sand. In order to pull it out, a horse, a rope, and a pair of triple blocks are used. If the horse exerts a steady pull of 200 pounds on the rope, and one block is fastened to a tree and the other to the machine, how much resistance can be overcome? Find two solutions for this problem, the rope being fastened in one case to the fixed block, and in the other to the movable block.

8. Two boys, *A* and *B*, are carrying a 100-pound load slung on a pole between them. Their hands are 10 feet apart, and the load is 3 feet from *A*. How much does each carry? Neglect the weight of the pole.

9. A man holds a shovelful of coal with his left hand at the end of the shovel and his right hand 22 inches away. Suppose the center of gravity of the shovel and coal to be 40 inches from his left hand, and the weight of the shovel and coal to be 50 pounds. How much does he push down with his left hand, and how much does he pull up with his right hand?

10. A man and a boy carry a load of 200 pounds on a pole 8 feet long. Where must the load be placed if the boy is to bear only 45 pounds of it?

11. How much must a boy lift on each handle of a wheelbarrow if the center of gravity of the 120-pound load is 15 inches from the axle and his hands are 25 inches farther away? Assume that the wheelbarrow weighs 50 pounds and has its center of gravity 12 inches from the axle. Compute also the force exerted by the axle.

12. What is the smallest number of pulleys required to lift a weight of 500 pounds with an effort of 100 pounds? How should they be arranged?

13. The hoisting derrick shown in figure 40 consists of a windlass with gears. The drum has a diameter of 8 inches and a large cogwheel with 60 cogs; the pinion, or small cogwheel, has 10 cogs, and the crank radius is 18 inches. What is the mechanical advantage of this double wheel and axle?

14. A bridge 100 feet long weighs 200 tons and has its center of gravity in the middle. A locomotive weighing 100 tons stands on the bridge with its center of gravity 40 feet from the north end. What is the total weight which the stone abutment at each end has to support?

Fig. 40. Hoisting derrick is a double wheel and axle.

Practical Exercise

Center of gravity of an automobile. Weigh an automobile. Find out how much of this weight is carried on the rear wheels. Compute how far back of the front axle the center of gravity is located. Can you think of any method of determining how high the center of gravity is above the ground?

32. Work. The function of every machine is to do a certain amount of work. Now in the technical language of science, **work means the overcoming of resistance.** For example (Fig. 41), a man does work when he lifts a trunk from the platform into a truck, or when he drags the trunk along the platform. But the man does not do work in the scientific sense of the word, no matter how hard he pushes or pulls, if he does not lift or move the trunk. In other words, work is measured by accomplishment, not by effort or by fatigue.

If we lift one pound a vertical distance of one foot, we are said to do **one foot pound** of work; if we lift 100 pounds 3 feet, we do 300 foot pounds of work; or if we exert a force

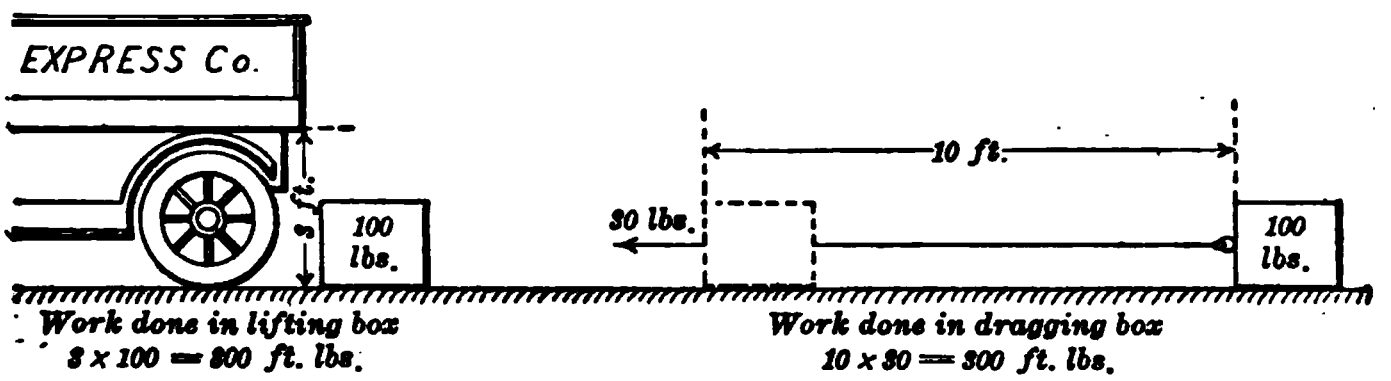

Fig. 41. Examples of doing work.

of 30 pounds on a 100-pound box and thus drag it 10 feet, we still do 300 foot pounds of work. In other words,

Work (foot pounds) = force (pounds) × distance (feet).

It should be remembered that the distance must be measured in the *same direction* as that in which the force is exerted.

FOR EXAMPLE, if a machinist exerts upon a file a force of 10 pounds downward and 15 pounds forward, how much work will he do in 40 horizontal strokes, each 6 inches long? Evidently the total distance is 20 feet and the *horizontal* force is 15 pounds; therefore the work done is 300 foot pounds. Since the downward push produces no motion but merely serves to produce friction between the file and the surface being filed, no work in the scientific sense is done by maintaining the downward push of 10 pounds.

33. Principle of work. In every machine a certain resistance is overcome by a certain effort exerted on another part of the machine. The principle of work, which applies to all machines where the losses due to friction may be neglected, may be stated as follows: *The work put into a machine is equal to the work got out.* In short,

Input = output.

FOR EXAMPLE, in the wheel and axle (Fig. 32) the *output* is equal to the weight times the distance it is lifted, and the *input* is equal to the effort times the distance through which it is exerted. For convenience, suppose the wheel makes just one turn. Then the distance the weight

is lifted is equal to the circumference of the axle, $2\pi r$, and the distance through which the effort is exerted is the circumference of the wheel, $2\pi R$. The *input* is $E \times 2\pi R$, and the *output* is $W \times 2\pi r$. Therefore, by the principle of work,

$$E \times 2\pi R = W \times 2\pi r$$

or

$$E \times R = W \times r,$$

which is exactly the equation got by considering the wheel and axle as a modified lever.

Another example is the system of pulleys shown in figure 36. The *output* is equal to the weight W times the distance it is lifted, and the *input* is equal to the effort E times the distance through which it is exerted. Suppose the distance the weight W is lifted is D, and the distance through which the effort E is exerted is d. The *output* is $W \times D$ and the *input* is $E \times d$. Then, by the principle of work,

$$W \times D = E \times d$$

or

$$\frac{W}{E} = \frac{d}{D}.$$

But when the weight is lifted 1 foot, it is evident that each of the supporting ropes must be shortened by 1 foot, and therefore E must move 4 feet; in other words,

$$d = 4\ D.$$

Substituting this value of d in the preceding equation, we have

$$\frac{W}{E} = 4,$$

which is the same as the result which we got in section 30.

PROBLEMS

1. How much work does a man do in lifting a 150-pound trunk into a truck which is 3.5 feet above the ground?

2. A man carries in baskets a ton of coal up 20 steps, each 7 inches high. How much work does he do on the coal?

3. In the metric system work is measured in kilogram meters. How much work is done in pumping 50 liters of water 40 meters high?

4. A horse weighing 1200 pounds draws a loaded wagon weighing one ton 10 miles in 4 hours. If the average pull exerted by the horse is 130 pounds, how much work does the horse do?

5. A girl weighing 125 pounds climbs to the top of Bunker Hill monument, which is 220 feet high. How much work does she do?

6. How much work does a man do in filling a 100-gallon water tank the average height of which is 30 feet above the well?

7. Experiment shows that it requires 50 pounds to push a 150-pound packing case along the floor. How much work is done in pushing this case 3 yards? in lifting it vertically 3 yards?

8. A man weighing 150 pounds pulls himself up a mast in a sling by means of a rope passing over a fixed pulley at the top of the mast. How much work does he do while rising 100 feet? How hard must he pull?

34. The differential pulley. In shops where heavy machinery is to be lifted, use is often made of the **differential pulley**, shown in figure 42. This consists of two sheaves of different diameters in the upper block rigidly fastened together, and one sheave in the lower block. An endless chain runs over these blocks. The rims of the sheaves of the upper block have projections which fit between the links and so keep the chain from slipping. Such a differential pulley has a *very large mechanical advantage*.

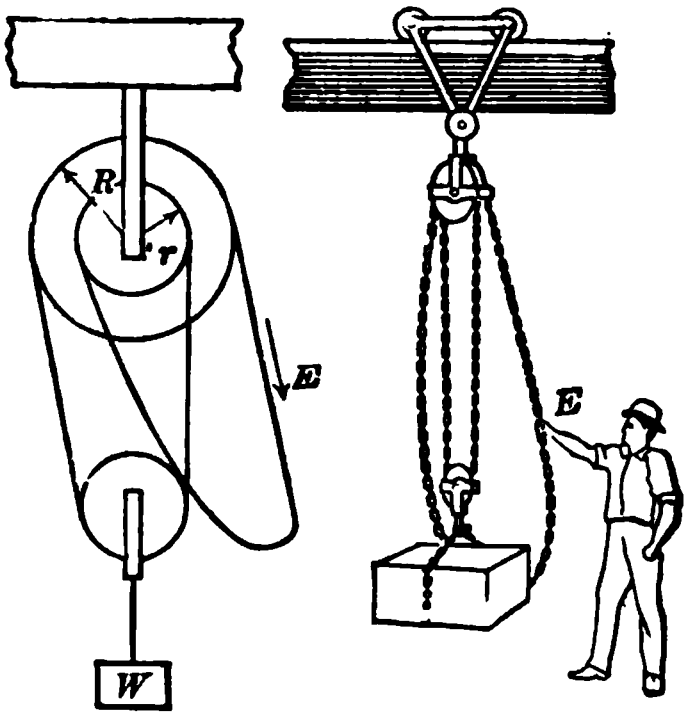

Fig. 42. Differential pulley.

To see just how it comes to have a large mechanical advantage, let us set up such a pulley and study it carefully. When the chain is pulled down as shown in the diagram, it is wound up faster on the large fixed pulley than it is unwound on the smaller pulley. In order to compute the mechanical advantage of the contrivance, let us suppose that E moves down far enough to turn the fixed pulley around once. If R is the radius of the large fixed pulley, then the work done by E will be $E \times 2\pi R$. If r is the radius of the small fixed pulley, then the length of chain unwound in one revolution will be $2\pi r$. The weight W will therefore be raised $\frac{1}{2}(2\pi R - 2\pi r)$, or $\pi(R - r)$, and the work done will be $W \times \pi(R - r)$. Therefore, if we neglect losses due to friction,

$$W \times \pi(R - r) = E \times 2\pi R$$

whence

$$\frac{W}{E} = \frac{2R}{R - r}$$

Since the difference between the radii of the two fixed pulleys $(R-r)$ is small, it is evident that the mechanical advantage is large.

The differential pulley has a second practical advantage in that there is always enough friction to keep the weight from dropping when the force E is released.

35. Inclined plane. Barrels and casks which are too heavy to lift from the ground into a wagon are often rolled up a plank or skid. This is an example of what is called an inclined plane. Every street or road which is not level is an example of an inclined plane. Experience teaches us that the steeper the incline, the greater the pull required to haul the load up the grade. In order to find out just how the effort and the weight or load are related to the grade, let us try a simple experiment where friction can be neglected.

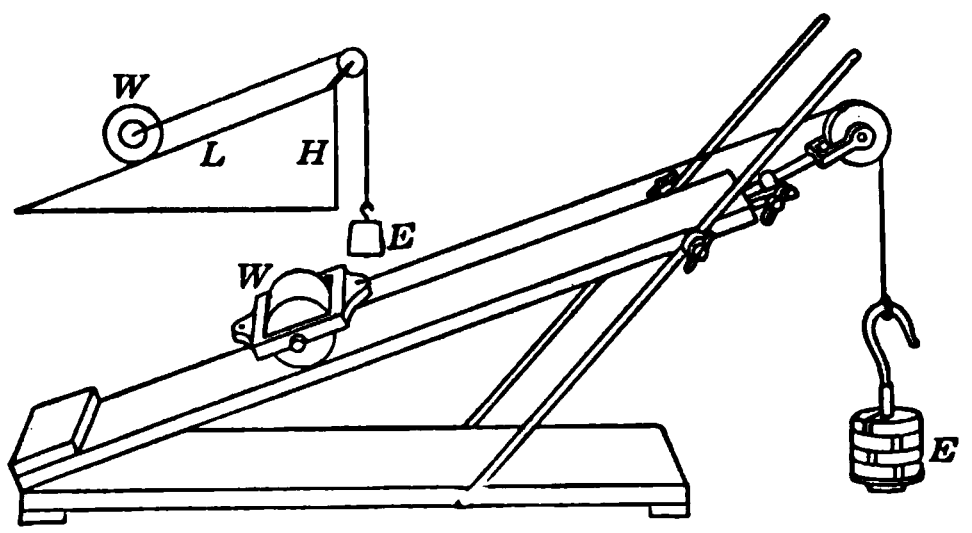

Fig. 43. Inclined plane.

Suppose we arrange a very smooth plane at an angle, as shown in figure 43. Let the weight or load W be a heavy metal cylinder which rolls with very little friction. Attach to the cylinder a cord and pass it over a pulley fastened to the top of the plane, and then hang on the other end enough weights to pull the load slowly up the inclined plane. You will find that the ratio W/E is approximately the same as the ratio L/H, where L is the length of the incline and H is its height.

From the general principle of work we can also arrive at this relation of resistance and effort to the length and height of the incline. Suppose the weight W is rolled from the bottom to the top of the incline. Then it has been lifted H feet, and the work done is W (pounds) times H (feet), or WH foot pounds. But while the weight W has been traveling up the

incline whose length is L, the effort E has moved L feet, and the work put in is equal to E (pounds) times L (feet), or EL foot pounds. Therefore, if we neglect friction, we have

$$W \times H = E \times L$$

or

$$\frac{W}{E} = \frac{L}{H}.$$

36. The grade of an incline. A civil engineer measures his distances horizontally and vertically, and when he speaks of a 1 per cent grade, he means an incline which rises 1 foot per hundred feet measured horizontally. In other words, *the grade of an incline is the ratio of the height to the base expressed as per cent.* For example, suppose a road rises 5 feet for every 100 feet measured horizontally, then this road is said to have a 5% grade. Since a 3% grade is the steepest allowable on a really good road, it is readily seen that a small force, such as can be exerted by a horse, can move a much heavier load up a gradual incline than could be lifted directly. For this reason the highways in mountain regions are laid out as zigzags and switchbacks. If we want a flight of steps easy to climb, we make the slope gentle.

Nevertheless it should be remembered that while the pull is less than the weight of the load, yet the distance the load travels is greater than when it is lifted straight up. In other words, what we gain in the amount of effort required we lose in the distance over which it must be exerted. The total work to be done is independent of the grade, except for the indirect effect of friction.

37. Wedge. If instead of pulling the load up the incline, we push the incline under the load, the inclined plane is called a **wedge.** Of course the smaller the angle of the wedge, the easier it is to push it in under the resistance. The fact that friction plays a very important part makes it impossible to state simply the relation between the effort required to force in a wedge and the resistance to be overcome.

All cutting and piercing instruments, such as the ax, the chisel, and the carpenter's plane, as well as nails, pins, and needles, act like wedges. The carpenter uses wedges to fasten the heads of hammers and axes on their handles. The woodsman uses wedges to split logs of wood.

In many machines rotating wedges, or cams, are used to exert pushes on rods. For example, a very common way of opening the intake and exhaust valves of an automobile engine is to arrange the valve stems, or rods, so that they are pushed up at the proper instant by a rotating cam, as shown in figure 44.

Valve

38. Screw. When an enormous force must be exerted, as in lifting a building, such machines as the lever and pulley will not do, because we cannot get enough mechanical advantage. A screw, such as the jackscrew, is used for this purpose.

Fig. 44. Cams used to open valves on automobile engine.

One form of jackscrew, used to lift the axle of an automobile, is shown in figure 45. The screw itself does not rotate, but the nut is slowly turned so as to raise the load. In one complete turn of this nut the screw is lifted the distance between two successive threads. The effort is applied at the end of the handle. The two equal bevel gears between the handle and the nut enable one to push downward instead of sidewise. They may be ignored and the handle thought of as attached directly to the nut.

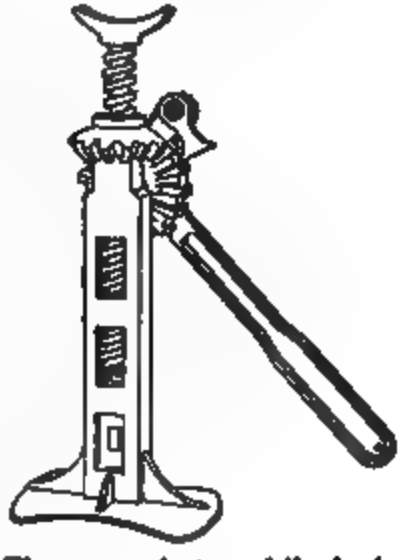

Fig. 45. Automobile jackscrew.

The **pitch** of a screw is the distance between two successive threads. In each complete turn of a screw the *output* is equal to the weight times the pitch, and the *input* is equal to the effort times the distance through which it acts; namely, the circumference of a circle made by the end of the handle.

If W equals the weight to be lifted and p (pitch) equals the distance between threads, the output for one turn is W

times p. Let E equal the effort or force applied on the handle, and $2\pi r$ equal the circumference of the circle in which it acts. Then E times $2\pi r$ is the input. Therefore, applying the principle of work to the machine, we have, if friction could be neglected,

$$W \times p = E \times 2\pi r$$

$$\frac{W}{E} = \frac{2\pi r}{p}.$$

In other words, *the mechanical advantage of the screw is equal to the ratio of the circumference of the circle moved over by the end of the lever, to the distance between the threads of the screw.*

As a matter of fact, friction consumes a large part of the work put in, and therefore the input is greater than the output. But this loss is not wholly a disadvantage, for friction keeps a screw from turning backward of itself.

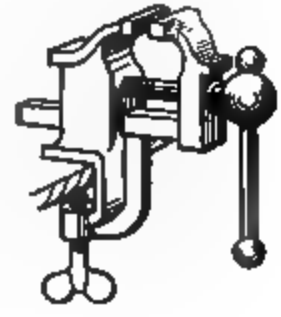

Fig. 46. Machinist's vise. The screw is turned by a lever.

39. Applications of the screw. We are all familiar with carpenters' **wood screws** and machinists' **bolts.** Most of us have seen a machinist's vise (Fig. 46), which uses a screw operated by a lever. Ordinarily, however, we do not think of the **propeller** of a boat or airplane as a screw, but it is. The propeller of a boat (Fig. 47), with its two, three, or four blades fastened to one end of the shaft, is driven by an engine at the other end. Its rotation is so rapid that the water has no time to get out of the way, and the propeller screws itself through the water like a wood screw through wood. Another example of the screw is

Fig. 47. Screw propeller on a boat.

the **micrometer screw** (Fig. 48), which is used to make very precise measurements. It contains an accurately turned thread of very small pitch, perhaps 1 millimeter. It is evident that if such a screw is turned $\frac{1}{100}$ of a complete turn, the spindle moves along its axis just 0.01 millimeters. This is the easiest way to measure so small a distance. The head is divided into 100 divisions, so as to indicate quickly and accurately the fraction of a revolution through which the screw has been turned.

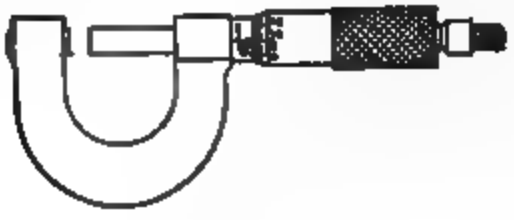

Fig. 48. A micrometer screw measures to 0.001 of a millimeter.

40. The worm gear. A worm gear is another device for getting a large mechanical advantage. It consists of a screw thread on a shaft which is tangent to a cogwheel, as shown in figure 49. One revolution of the shaft rotates the cogwheel the distance between two cogs. Therefore, if the cogwheel has n teeth, the shaft turns n times as fast as the wheel. Thus the mechanical advantage of such a worm gear is equal to the number of teeth on the wheel.

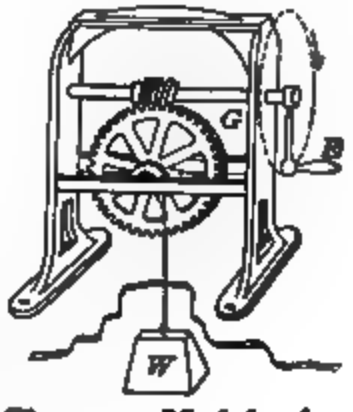

Fig. 49. Model of a worm gear.

This device is commonly used to drive the rear axles of automobile trucks (Fig. 50), and also to reduce the speed in speed counters.

41. Combinations of simple machines. What is called a single machine in factories and shops is usually a combination of the simple machine elements described above. That is, it is a more or less complicated collection of levers, pulleys, wheels, axles, screws, and gears.

Fig. 50. Worm gear as used on the rear axle of a truck.

To show how such a machine may be analyzed into its elements, let us, as it were, dissect a crane, or derrick,

(Fig. 51) such as is used in unloading freight cars, or in hoisting building material into place.

The movable pulley to which W is attached gives a mechanical advantage of 2; the fixed pulley at the end of the boom merely changes the direction of the pull; the wheel F and its axle G give a mechanical advantage equal to the ratio of the size of the wheel to the size of the axle. A third mechanical advantage is gained in the wheel and axle, D and E, a fourth advantage is gained in B and C, and finally there is the mechanical advantage of the crank P and the axle A. The total mechanical advantage of this compound machine is the product (*not* the sum) of the separate advantages gained by its separate elements.

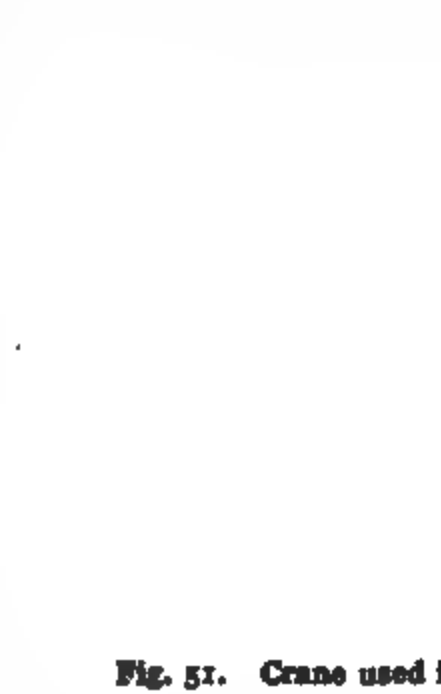

Fig. 51. Crane used in freight yards.

In general, then, *to compute the mechanical advantage of any compound machine, first find the mechanical advantage of each separate element and then find the product of the separate advantages.* Sometimes it is simpler to compute the mechanical advantage as the ratio of the distance the effort moves to the distance the resistance or load moves in the same time. This ratio is known as the velocity ratio.

Problems

(Friction is to be neglected in all these problems.)

1. What force will be needed to pull a weight of 200 pounds slowly up a slope which rises 1 foot in 25 feet measured along the slope?

2. If the approach to a bridge rises 1 foot in 10 feet of length, how heavy a load can be drawn up by a horse that can exert a pull of 150 pounds?

3. A boy wants to roll a 200-pound barrel of flour into a cart 4 feet above the ground. He can push with a force of 80 pounds. (*a*) How long a plank will he need? (*b*) How much work does he do?

4. An effort of 40 pounds acting parallel to an inclined plane is required to keep a 250-pound cake of ice from sliding down. What is the ratio of the length to the height of the plane?

5. A test shows that it takes 500 pounds more force to haul an electric car weighing 4 tons up a certain grade than to haul it along a level. What is the grade?

6. What weight can be raised by a builder's jackscrew (Fig. 52) when a force of 40 pounds is applied at the end of a lever arm 2 feet long, the pitch of the screw being 0.3 inches?

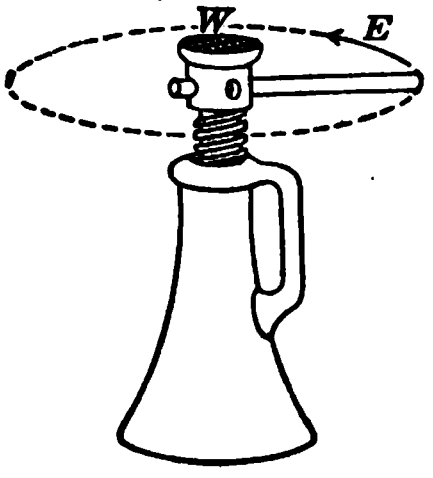

Fig. 52. Builder's jackscrew.

7. The lever in a jackscrew extends 2 feet from the center. If a man is able to lift 25 tons by exerting a pressure of 100 pounds, how many threads to the inch must there be?

8. In the preceding problem, what is the mechanical advantage?

9. The pitch of the screw of a bench vise (Fig. 46) is 0.2 inches and the handle of the screw is 7 inches long. What force could be exerted by the jaws of the vise if a force of 25 pounds were applied at the end of the handle?

10. In the worm gear shown in figure 49, the wheel G has 98 teeth, and its drum is 8 inches in diameter. The worm is turned by a crank handle E which is 15 inches long. (*a*) What is the velocity ratio? (*b*) How great a weight W could be lifted by an effort of 20 pounds?

11. In the crane shown in figure 51, the weight W is 5 tons, and the radii of the four small cogwheels are assumed to be equal and each 1/5 the radius of the crank P and of the wheels B, D, and F, which are also assumed to be equal. (*a*) What is the mechanical advantage of the whole machine? (*b*) What force must be applied at P?

12. The pedal of a bicycle is halfway down and is pressed down with a force of 100 pounds. The crank arm is 6 inches long, and the sprocket wheel is 8 inches in diameter. Find the tension or pull on the chain.

13. In the preceding problem the sprocket wheel attached to the rear wheel is 2.5 inches in diameter, and the wheel is 28 inches in diameter. (*a*) How far does the bicycle go when the pedal makes one complete revolution? (*b*) How much does the tire of the rear driving

wheel push backward on the roadbed when the man presses 100 pounds on the pedal?

Practical Exercise

Automobile jack. Borrow several types of automobile jacks and measure the mechanical advantage of each. Is a large mechanical advantage a real advantage?

42. Work and power. The words "work" and "power" are often confused or interchanged in colloquial use. The term "work," in physics, means the overcoming of resistance. For example, if a boy carries a pail of water weighing 50 pounds up a flight of stairs 12 feet high, he does 600 foot pounds of work. The amount of *work* done would be the same whether he did this in one minute or one hour, but the amount of *power* required to do this job in one minute would be 60 times the power required to do it in one hour. The term "**power**" adds the idea of time. *Power means the speed or rate of doing work.*

43. Horse power. The earliest use of steam engines was to pump water from mines. This work had previously been done by horses; so the power of the various engines was estimated as equal to that of so many horses. To make this idea definite, James Watt carried out some experiments to determine how many foot pounds of work a horse could do in one minute. He found that a strong dray horse working for a short time could do work at the rate of *33,000 foot pounds per minute, or 550 foot pounds per second.* This rate is therefore called a **horse power.** To get the horse power of an engine, compute the number of foot pounds of work done per minute and divide by 33,000, or per second and divide by 550.

$$\text{Horse power (H.P.)} = \frac{\text{foot pounds per minute}}{33000}$$

$$= \frac{\text{foot pounds per second}}{550}.$$

For example, an engine is used to pump 10,000 gallons of water per hour into a reservoir 50 feet above the supply. How much horse power is required?

One gallon of water weighs 8.34 pounds; so 10,000 gallons of water weigh 83,400 pounds. The work done in lifting this weight 50 feet is $83{,}400 \times 50$, or 4,170,000 foot pounds. Since this is done in one hour, the work per minute is $\frac{4\,170\,000}{60}$, or 69,500 foot pounds. The horse power required would be $\frac{69\,500}{33\,000}$, or 2.1 H.P.

44. Transmission of power. In any shop containing several machines one easily distinguishes two kinds — the *driving machines*, which may be steam or oil engines, water wheels, or electric motors, and the *driven machines*, such as lathes, drills, planers, and saws. There must always be some connecting link between a driving and a working machine; that is, some means of *transmission*. If these machines are not far apart, the common method is to use shafting, belts, chains, or cogwheels; but when the prime mover and the driven machine are widely separated, sometimes even miles apart, some form of electrical transmission is used. Electrical transmission will be explained in Chapter XVIII.

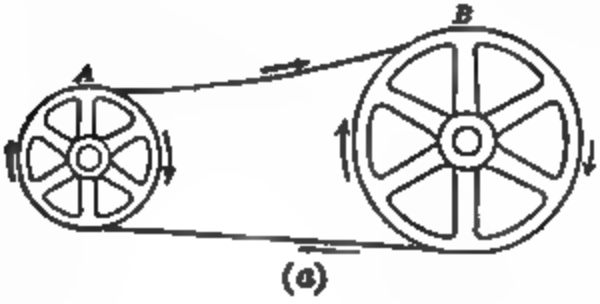

Fig. 53. Transmission of power by belt.

When a belt, rope, cable, or endless chain is used, it passes over two pulleys, as shown in figure 53. In case (*a*) the pulleys rotate in the same direction, while in case (*b*), where the belt is crossed, they rotate in opposite directions. It is evident that if the circumference (or diameter) of the large pulley is n times as great as the circumference (or diameter) of the small pulley, the latter will turn n times as fast as the large pulley.

The same is true of cogwheels, and since the teeth on the perimeters of two interlocking wheels must be the same size, it follows that the *number* of cogs on each wheel is a measure

of its circumference. The speeds of two such wheels are inversely proportional to the number of teeth on them. Just as in the case of two pulleys with a crossed belt, two cogwheels rotate in opposite directions.

Problems

1. If it takes 22 pounds to pull a 200-pound sled along a level road covered with snow, how much work is done in dragging the sled 50 feet?

2. In the preceding problem, if the sled is drawn at the rate of 4 miles an hour, how many horse power are required?

3. How much work can a 5-horse-power engine do in 10 minutes?

4. Which does more work in a week, a 500-horse-power engine that runs 8 hours a day, or a 200-horse-power engine that runs all the time?

5. What is the horsepower of an elevator motor, if it can raise the car with its load, 1500 pounds in all, from the bottom to the top of a 100-foot building in 10 seconds?

6. In what time would you have to pull a 50-pound bucket of water up a well 33 feet deep in order to be working at the rate of $\frac{1}{2}$ horse power?

7. An airplane with a 300-horse-power engine makes 60 miles an hour. What is the thrust of the propeller?

8. A locomotive pulling a train along a level track at the rate of 25 miles an hour expends 750 horse power. Find the total resistance overcome.

9. A motor has a 4-inch pulley which is belted to a 16-inch pulley on an overhead shaft. The motor is making 1800 revolutions per minute. What is the speed of the overhead shaft?

10. A certain air compressor should run at 240 r. p. m. and it has a 50-inch pulley. An electric motor is available and runs at 1200 r. p. m. How large a pulley should be fitted to the motor?

11. In an electric-car motor a pinion, or small cogwheel, attached to the armature shaft has 20 cogs, and the gear wheel attached to the car axle has 36 cogs. If the car wheel is 33 inches in diameter, find the number of revolutions the motor makes while the car goes 100 feet.

12. An automobile with 30-inch rear wheels is going 20 miles an hour. The gear ratio of the differential ($B : P$ in Fig. 54) is 3.63. How many revolutions per minute (r. p. m.) is the engine making?

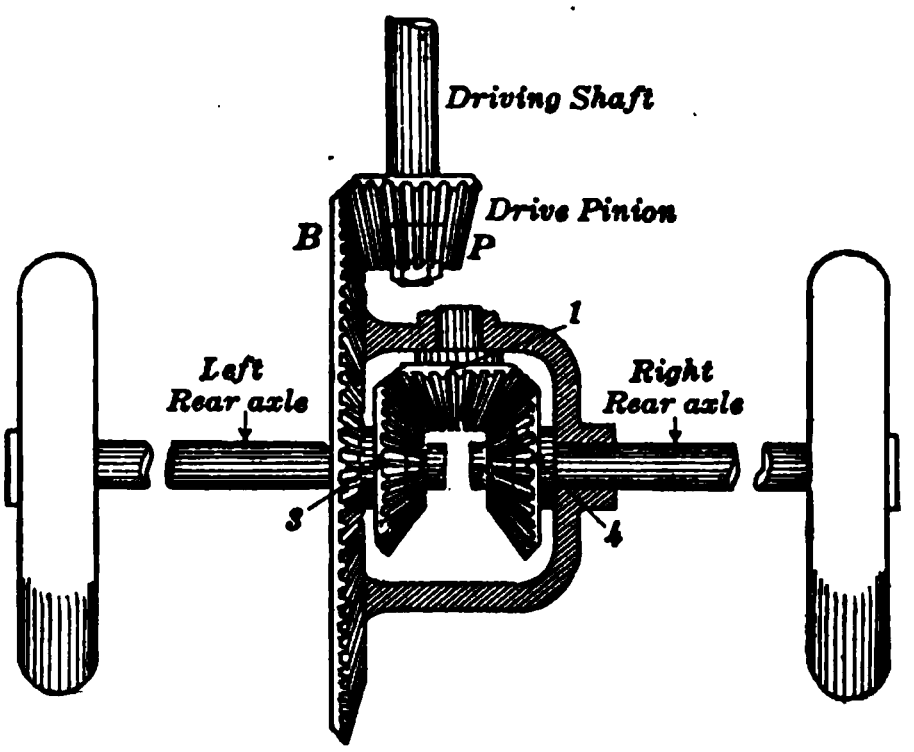

Fig. 54. The differential on an automobile changes the direction of motion and makes the two rear wheels independent.

13. If the same engine, running at the same speed, is connected with the rear wheels through a worm gear which has 30 teeth on the gear wheel, what is the speed of the car in miles per hour?

Practical Exercises

1. The horse power of a man. Measure the vertical height of some long flight of steps. Determine with a stop watch how long it takes you to run up. Compute the work done in lifting your own weight this vertical distance and from this get your horse power. Get your friends to try this experiment.

2. Power to operate household machines. Find out how much horse power you can put forth while turning something like a bread mixer or ice-cream freezer. (Hint. Use a spring balance to measure the pull required, both at the beginning and at the end of your experiment, and use the average. Also measure the radius. Then see how many turns you can make in 1 minute.)

45. Friction. What we have thus far said about machines has been on the assumption that friction could be neglected. Often, however, friction plays a very important part in the operation of a machine, sometimes detrimentally and sometimes to our great advantage. We may, therefore, profitably inquire what friction is and how it acts, what determines its magnitude, and how it affects what a machine can do.

By friction we mean *the resistance which opposes every effort to slide or roll one body over another.*

46. Friction often a help. Many machines, devices, and processes depend upon friction for their successful operation. Without friction belts would not cling to their pulleys, automobile, street-car, and railroad brakes would not work, ropes could not be made, and nails, screws, and matches would be useless. Even walking would be impossible, as any one can see who has tried to run on a highly polished floor or on ice.

No railroad train or automobile could move without friction, because it is the **traction**, or friction, between the driving wheels and the rail or road that pushes them forward. It is to increase the traction that the surfaces of automobile tires are often made with knobs or irregular projections that bite into soft roads, or with little suction cups or cavities that tend to stick to smooth pavements. On wet days automobilists also use chains (Fig. 55) to increase their traction, and locomotive drivers sprinkle sand on the tracks just in front of their wheels. Good traction is quite as important in stopping as in starting an automobile or a train. When automobile wheels slip at all, they are likely to slip sidewise as well as forward; this is called **skidding**. It is dangerous because the automobile is temporarily quite out of control. To avoid it, drive slowly around corners or through sand, and use chains in wet weather.

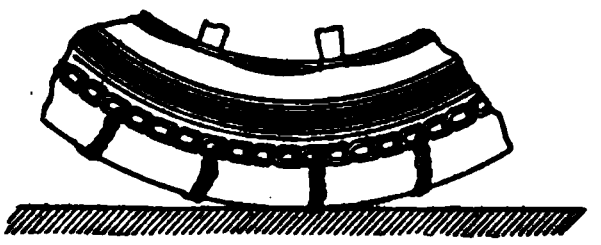

Fig. 55. Chains on automobile wheels tend to prevent skidding.

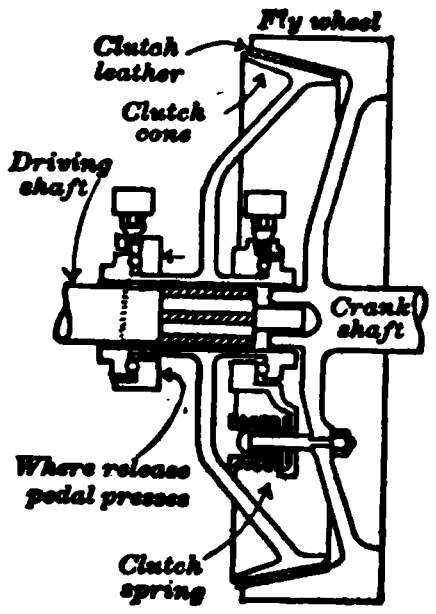

Fig. 56. Cone clutch, which joins the engine to the driving shaft.

47. Friction clutches. Furthermore, automobile engines deliver their power to the driving shaft through some sort of friction clutch. In the **cone clutch** (Fig. 56) a leather-faced cone is pushed into the tapered rim of the flywheel by springs. In the **multiple disk clutch** (Fig. 57) there is a series of metal disks arranged in two groups. Every other disk

is a driving disk that turns with the flywheel; the alternate, or driven, disks are attached to the main shaft. When the driving and driven disks are pressed together by the clutch springs, the driving disks drag the others around with them. We see, then, that in both cases the power is transmitted entirely through friction contacts. When the driver wants to stop the car, he releases the clutch by pushing a foot pedal. This takes off the thrust of the clutch springs and lets the disks separate, so that the driving disks can rotate independently of the driven disks. The cone clutch releases in a similar manner.

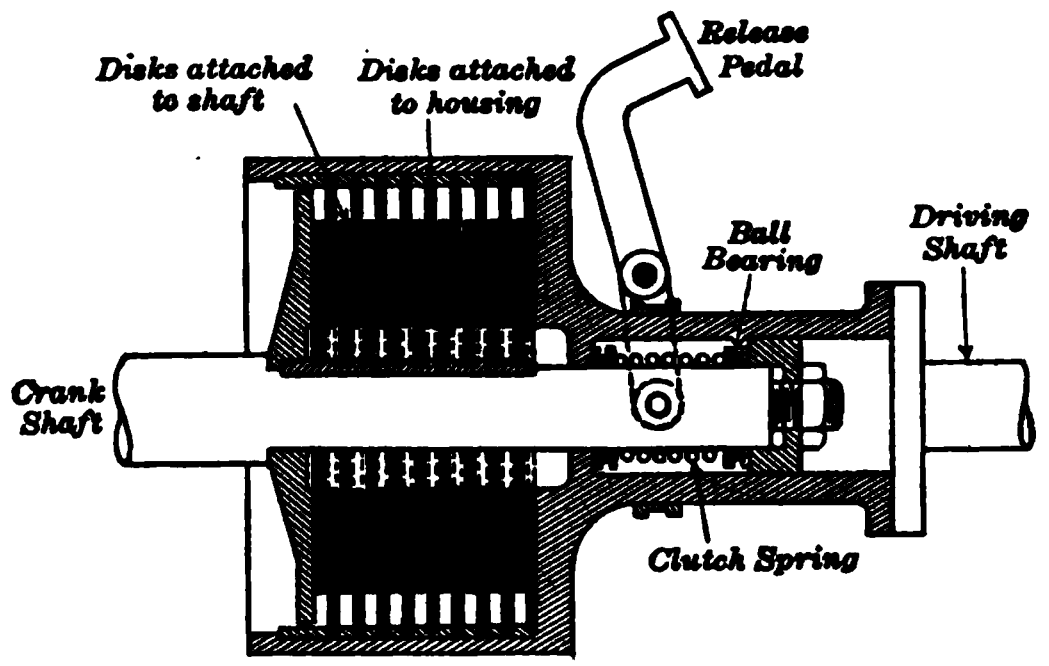

Fig. 57. Multiple disk clutch. Every other disk is joined to the engine; the rest are joined to the driving shaft.

48. Factors affecting friction. The factors which determine the amount of friction in any particular case are so numerous and uncertain that only the most general principles can be stated positively. In general, friction depends on *velocity*, on the nature and condition of the rubbing *surfaces*, and on the *load*.

49. Effect of velocity on friction. It is commonly said that *friction does not depend much on velocity*, and this is approximately true. Nevertheless, *starting* friction is distinctly greater than *sliding* friction, as anyone can see who pulls a box or heavy block of wood across a table top with a spring balance. This is why a locomotive can start a heavy train if the driving wheels are not allowed to slip; whereas if they slip at all, they spin rapidly without doing much good. Furthermore, friction usually *decreases* somewhat with *increasing speed;* thus the friction between the brake shoes and the wheels of railroad cars is only one third to one half as great at 60 miles an hour as at 20 miles an hour. This is why an engineer

or motorman lessens the pressure of his brakes as his train or car slows down.

50. Effect of surfaces on friction: lubrication. On the other hand, *friction depends very much on the nature and condition of the rubbing surfaces.* Friction is less when the surfaces are smooth and hard. Thus two well-finished metal surfaces may show only about half as much friction as two wooden surfaces under the same conditions, and these only about half that of two unpolished stone surfaces.

Friction is also much diminished by proper **lubrication.** Soap or paraffin rubbed on a bureau drawer that sticks may make it much easier to move. Two well-oiled or greased metal surfaces may show only $\frac{1}{4}$ or even $\frac{1}{8}$ as much friction as the same surfaces when dry. This is why it is so important to attend to the lubrication of all sorts of machines, not only the large machines in shops, but also sewing machines, bicycles, windmills, agricultural machinery, farm engines, and particularly automobiles. People seem to forget that an automobile should be supplied with oil and grease just as faithfully and *regularly* as with gasoline. If this is not done, the increased friction in the various bearings and in the cylinders makes them wear much faster. Sooner or later, also, a bearing "burns out." This means that the surface of the bearing, which is made of a whitish, easily melted metal called Babbitt metal, melts or tears out, leaving a rough surface and a very loose fit. Then the engine "knocks," and the shocks may break a connecting rod and wreck everything. Or sometimes a bearing or a piston may "freeze," which means that the shaft or piston has expanded with the heat until it has stuck fast and stopped the machine. "Hot boxes" on railroads are familiar examples of what happens when something goes wrong with lubrication.

Not only should every machine get frequent lubrication but each part should have *the right kind of lubricant.* Thus, automobile wheel bearings need grease, the differential needs a heavy semi-solid oil mixture, the crank case a suitable grade of cylinder oil, and the leaves of the springs an oil and graphite paste. A watch bearing, on the other hand, needs the best grade of light pure sperm oil. Detailed directions about lubrication are supplied with all valuable machines, and these directions should be scrupulously followed.

51. With dry surfaces friction does not depend much on the area of contact. That is, it takes about the same pull to drag

a brick-shaped block across a table top when the block is standing on end, as when it is lying on its side. On the other hand, *with well-lubricated surfaces friction is nearly proportional to the area of contact.*

52. Effect of load on friction: coefficient of friction. When a box is loaded, it requires much more force to pull it along than when it is empty. In fact, the force needed to slide a given box over a certain floor is just about doubled when the total weight of the box and its contents is doubled, and tripled when the weight is tripled. In many cases the rubbing surfaces are not horizontal and the force pushing them together is not a weight; but here also the backward drag due to friction doubles or triples whenever one doubles or triples the perpendicular force with which the rubbing surfaces press against each other. In general, *the force needed to overcome friction is nearly proportional to the total normal pressure;* that is, the fraction — friction divided by total normal pressure — is nearly constant for a given pair of surfaces, no matter what the load. This fraction is called the coefficient of friction.

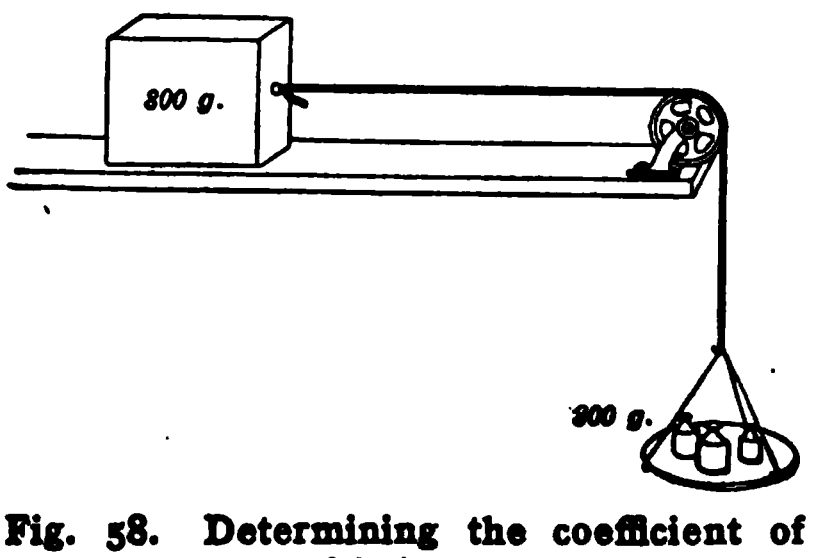

Fig. 58. Determining the coefficient of friction.

$$\textbf{Coefficient of friction} = \frac{\textbf{force of friction}}{\textbf{total normal pressure}}.$$

For example, suppose a block weighing 800 grams is dragged slowly along a horizontal board by a force of 300 grams, as shown in figure 58. Then the coefficient of friction is $\frac{300}{800}$, or 0.375.

Often the coefficient of friction that applies to a given case is at least approximately known from engineering handbooks or previous experience. Then the force of friction can be computed by means of the equation,

Force of friction = coefficient of friction × total normal pressure.

For example, if the weight carried by the driving wheels of a certain locomotive is 160,000 pounds, and the coefficient of friction between the wheels and the track is known to be about 0.25, the maximum pull which the locomotive can exert before its wheels slip is 0.25 × 160,000, or 40,000 pounds.

53. Efficiency of machines. In the first part of this chapter we assumed that we were dealing with ideal or perfect machines, where friction plays no part. In such cases *the output equals the input* of work. But in every actual machine friction causes a loss or waste of work. It takes some input of work merely to keep the machine moving, even when its useful output is zero. The useful work done by a machine is consequently always less than the work put into it, and the principle of work may be stated in the form,

$$\textbf{Output} = \textbf{input} - \textbf{work lost by friction.}$$

The ratio of the output of a machine to its input is called the ***efficiency*** of the machine. It is always less than one, and is usually expressed as a percentage; that is, the output is a certain percentage of the input delivered to the machine. Output and input may be expressed in *work* units or in *power* units.

$$\textbf{Efficiency} = \frac{\textbf{output}}{\textbf{input}} = \frac{\textbf{work done by machine}}{\textbf{work done on machine}},$$

or $$\textbf{Output} = \textbf{efficiency} \times \textbf{input.}$$

For example, with a certain block and tackle it is found that a force of 125 pounds is necessary to lift a weight of 500 pounds, and the force must move 6 feet in order to raise the weight 1 foot. What is the efficiency of this block and tackle?

The *output* $= 1 \times 500 = 500$ ft. lbs. and
the *input* $= 6 \times 125 = 750$ ft. lbs.

Therefore the efficiency is $\frac{500}{750}$, or 0.667, or 66.7%.

The efficiency of a lever where the friction is very small is nearly 100%, but in the commercial block and tackle it is sometimes less than 50%, and in the jackscrew the friction is so large that the efficiency is often as low as 25%.

Friction in machines can be diminished, and efficiency increased, by using ball or roller bearings. The chief objection to them is their high cost.

Problems

1. A tool is pressed on a grindstone with a force of 25 pounds; the coefficient of friction is 0.3. What is the backward pull of friction?

2. The coefficient of friction between the driving wheels of a locomotive and the rails is 0.25. How much weight must be carried on the driving wheels if the locomotive is to exert a pull of 15 tons?

3. A test shows that it takes a force of 17 pounds to pull on ice a man weighing 150 pounds. What is the coefficient of friction?

4. In lifting a 1250-pound block of marble to a height of 90 feet, the hoisting engine did 125,000 foot pounds of work. What was the efficiency of the hoist?

5. What load can a pair of horses, working at the rate of 2 horse power, draw along a level highway at the rate of 3 miles an hour, if the coefficient of friction between the sled runners and the ice-covered road is 0.02?

6. It takes a pull of 150 pounds to haul a load of one ton up an inclined plane which rises 5 feet in 100 feet along the incline. What is the efficiency?

7. A motor whose efficiency is 90% delivers 5 horse power. What must be the input?

8. What is the efficiency of a pump which can deliver 250 cubic feet of water per minute to a height of 20 feet, if it takes a 10-horse-power engine to run it?

9. A centrifugal pump is designed to deliver 50,000 gallons of water per minute at a height of 10 feet, and has an efficiency of 70%. What should be the horse power of the steam turbine chosen to drive it?

10. A steam shovel driven by a 6-horse-power engine lifts 200 tons of gravel to a height of 15 feet in an hour. How much work is done against friction?

11. A builder's jackscrew (Fig. 52) is used to lift 10 tons. There are 5 threads to the inch and the radius of the effort-arm is 2 feet. The efficiency of the screw is 40%. How great a pull is required?

12. If a 400-horse-power hoisting engine can pull a ton of ore up a mine shaft a mile deep in 1 minute, what is the efficiency of the machinery?

SUMMARY OF PRINCIPLES IN CHAPTER II

The principle of moments—used in solving all kinds of levers, straight and bent, the wheel and axle, etc.:

Effort × its lever arm = resistance × its lever arm.

To get force on fulcrum or to solve a pulley system,

Sum of forces up = sum of forces down.

$$\textbf{Mechanical advantage} = \frac{\textbf{resistance}}{\textbf{effort}} = \frac{\textbf{effort distance}}{\textbf{resistance distance}}.$$

Laws of equilibrium, applicable to any object *at rest* under the action of two or more forces:

(1) Sum of forces in any direction = sum of forces in opposite direction.

(2) Sum of moments clockwise around any point = sum of moments counterclockwise around same point.

The principle of work:

Work (foot pounds) = force (pounds) × distance (feet).

In any *frictionless* machine,

Output = input.

If there is *friction*,

Output = input − work lost by friction.

Power = rate of doing work.

1 horse power = 550 foot pounds per second,
= 33,000 foot pounds per minute.

$$\textbf{Coefficient of friction} = \frac{\textbf{force of friction}}{\textbf{total normal pressure}}.$$

Force of friction = coefficient × total normal pressure.

$$\textbf{Efficiency} = \frac{\textbf{output}}{\textbf{input}} = \frac{\textbf{work done by machine}}{\textbf{work done on machine}}.$$

Output = efficiency × input.

QUESTIONS

1. Make a list of a dozen applications (not mentioned in this book) of the simple machine elements described in this chapter that you have seen outside of the classroom within a week. Make a simple sketch of each.

2. Distinguish between the popular use of the term "work" and its technical use in physics and engineering. Give an example of "work" that is not technically "work."

Fig. 59. Ball bearings used in a bicycle.

3. What simple machine elements do you find in the following machines: clothes wringer, broom, ice-cream freezer, plow, grindstone, and rotary meat chopper.

4. Distinguish between the terms "mechanical advantage" and "efficiency." Illustrate by an example.

5. Is there any mechanical advantage in an equal-arm lever? Why is it often used in machines? Why is an unequal-arm lever useful?

Fig. 60. Platform scales illustrating a combination of levers.

6. Figure 59 shows the way in which ball bearings are used in a bicycle pedal. Explain how this device diminishes friction. Where are roller bearings used in an automobile?

7. Show how the principle of work applies to the lever.

8. Figure 60 shows the construction of the ordinary platform scales. Notice that it is merely a combination of levers. Identify the fulcrum of each lever. Explain why the load to be weighed may be placed anywhere on the platform.

9. Why are you apt to twist off the head of a small screw by using a screwdriver in a bit brace?

10. When a machinist speaks of "an 8–32 screw," what does he mean?

11. What determines the "angle of repose," or slope, of the rock waste, or talus, at the base of a cliff?

12. Why are the modern air brakes on cars more effective than the old-fashioned hand brakes?

13. Why can a pair of horses draw a heavier load along a hard, smooth road than over a muddy or sandy road? (Look up rolling friction.)

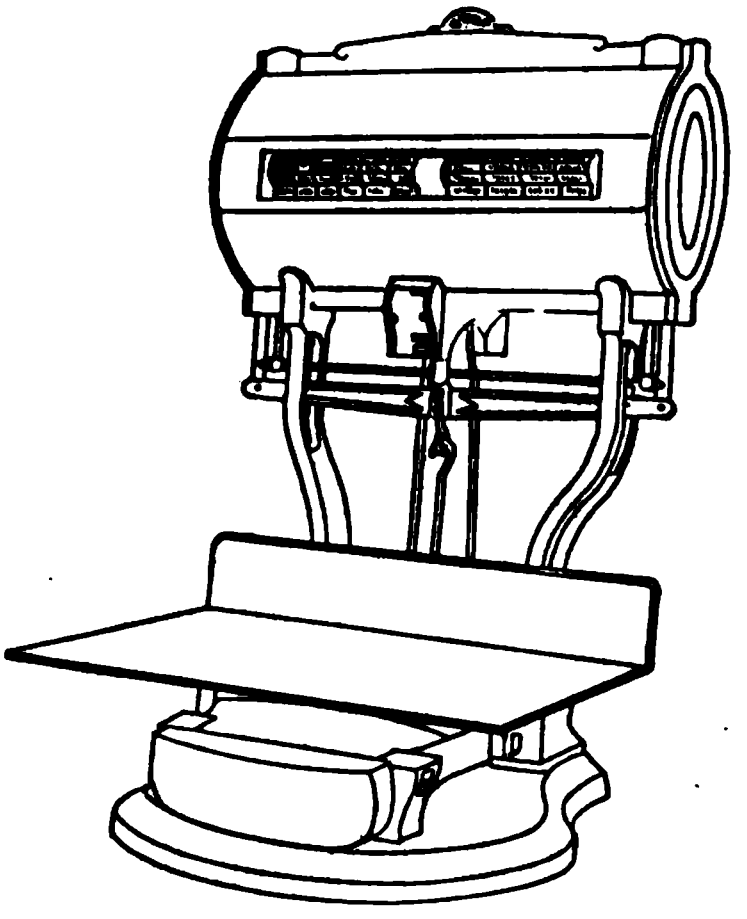

Fig. 60 A. Computing scales.

14. Why is it better in stopping a train or an automobile not to apply the brakes so hard that the driving wheels are held fast and merely slide?

PRACTICAL EXERCISES

1. Efficiency of automobile jacks. To get a load of several hundred pounds, place a long timber (perhaps 8 feet long and 2 by 4 inches) across the jack. Put a weight of 50 pounds on one end of the timber and place the jack at a short distance (1 to 2 feet) from the other end, which is fastened down. Measure the effort required to lift the load. Compute the efficiency of the jack under several loads.

2. Computing scales. Describe the construction of the computing scales shown in figure 60 A, which are often found in grocers' shops and meat markets. Explain how they work.

CHAPTER III

MECHANICS OF LIQUIDS

Machines using liquids — force and pressure — pressure in a liquid due to its weight — levels of liquids in connecting vessels — Pascal's principle of transmitted pressure — applications in presses — upward pressure of liquids — Archimedes' principle and its applications — specific gravity of solids and liquids — city waterworks, hydrants, faucets, gauges, and meters — water wheels — cohesion and adhesion — capillarity.

54. Machines using liquids. Some machines involve more than the levers, pulleys, screws, gears, and other simple elements that we studied in Chapter II. For instance, water wheels, hydraulic presses, and hydraulic jacks make use of liquids. Furthermore, ships float, anchors sink, and submarines do either at the will of their commanders, in accordance with certain laws that deal with liquids.

Finally we shall learn how certain principles of the mechanics of liquids are involved in the operation of city fire departments, waterworks, and sewage systems.

55. Force and pressure. In studying liquids we must distinguish carefully between force and pressure. **Force** means a *push* or *pull*. Forces are usually expressed in pounds or grams or kilograms. **Pressure** means the *push or pull per unit area* of the surface acted upon. That is,

$$\textbf{Pressure} = \frac{\textbf{force}}{\textbf{area}},$$

$$\textbf{Force} = \textbf{pressure} \times \textbf{area}.$$

Pressures are usually expressed in pounds per square inch, or in grams per square centimeter.

56. Pressure in a liquid due to its weight. Water standing in a cylindrical open-topped tank (Fig. 61) exerts a force on the bottom of the tank because the water is heavy. The total force against the bottom is the total weight of the water. The pressure is the weight of so much of the water as rests on one square foot or one square centimeter of the bottom. This water can be thought of as forming a little column extending from the bottom of the tank to the surface of the water, and with a cross section of just one square foot or one square centimeter. The volume of this column is numerically equal to its height, that is, to the depth of the water; and the weight of the column is its volume times its density; this weight is the pressure at the bottom. Evidently for liquids in open tanks or vessels,

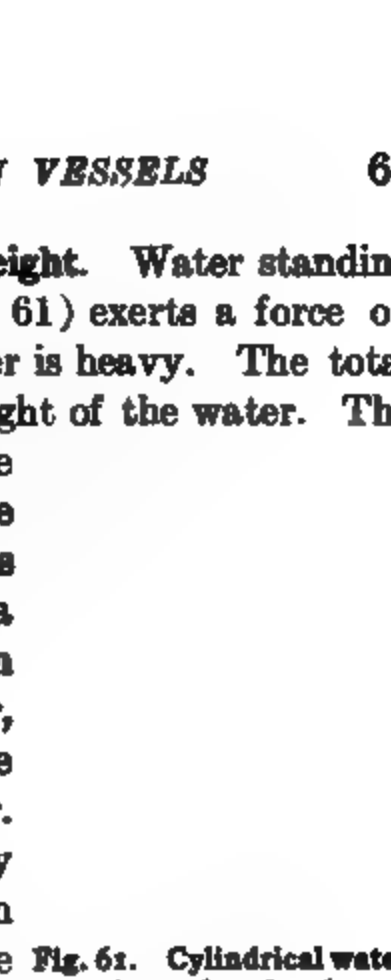

Fig. 61. Cylindrical water tank made of redwood staves.

$$\text{Pressure} = \text{depth} \times \text{density},$$
$$\text{Total force} = \text{area} \times \text{depth} \times \text{density}.$$

FOR EXAMPLE, suppose we have a box the bottom of which is 10 centimeters by 20 centimeters, and which is 15 centimeters deep.

If the box is full of water, each square centimeter of the bottom supports a column of water 15 centimeters tall, weighing 15 grams, and the pressure on the bottom is 15 grams per square centimeter. The total downward force on the bottom would be $200 \times 15 \times 1$, or 3000 grams.

If the box is filled with mercury instead of water, each square centimeter supports a column of mercury the volume of which is, as before, 15 cubic centimeters. But since one cubic centimeter of mercury weighs 13.6 grams, this column weighs $15 \times 13.6 = 204$ grams, and the pressure is 204 grams per cubic centimeter. The total force on the bottom would be $200 \times 15 \times 13.6$ grams, or 40.8 kilograms.

57. Downward pressure in differently shaped vessels. So far we have considered vessels with vertical sides. In the ordinary pail, however, the sides are not vertical, but flare

outward as in case *B* in figure 62. Perhaps one might expect that the pressure on each square centimeter of the bottom would be greater than in case *A*, because there is so much more water in the vessel. This, however, is not true. Each square centimeter of the bottom has to hold up only the little column of water above it, just as it did in case *A*. The extra water above the slanting sides is held up by those sides and

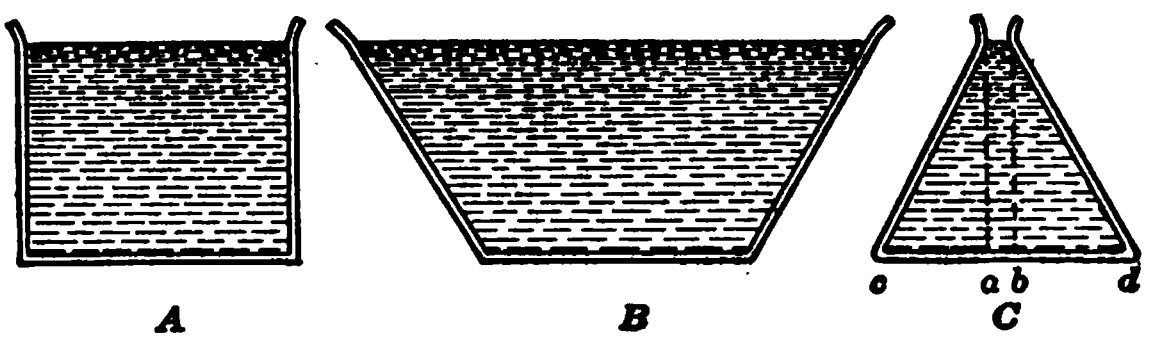

Fig. 62. Vessels with variously shaped sides. *A*, vertical; *B*, flaring; *C*, conical.

not by the bottom. If the area of the base and the depth of liquid are the same in *A* and *B*, the total downward push of the liquid on the bottom will be the same, even though *B* holds more liquid than *A*.

In case *C* the depth of liquid and area of base are the same as in cases *A* and *B*, but the top is smaller than the base. It is easy to see that the pressure on that portion of the base *ab* directly under the top would be the same as in the other vessels, but it might at first seem that the pressure would gradually decrease as we go from *a* to *c* and from *b* to *d*. But this is not true. Just as, when the sides slope outward, they hold up the excess of water, so, when they slope inward, they push down enough to make up for the deficit in water. In all three cases in figure 62, the pressure and total force on the bottom are the same; that is, *the downward pressure of a liquid is independent of the shape of the vessel.*

Figure 63 shows an ingenious apparatus similar to that invented by Pascal in France to illustrate these principles. A vessel of any desired shape screws into a base ring carrying a thin, corrugated metal disk that serves as the bottom of the vessel. When water in the vessel

exerts a pressure on this disk, the center of the disk deflects slightly like a spring and turns the pointer on the dial by means of a rack and pinion. We have thus a sort of spring balance for measuring the pressure on the bottom of the vessel. The tank *T*, which can be raised and lowered, and the flexible connecting tube afford an easy means of filling and emptying the vessel *C*.

By using vessels of different shapes on this apparatus, we can show that when the depth is the same the pressure on the bottom is also the same, no matter what the shape of the vessel. Furthermore, by filling a vessel slowly, we can show that the pressure increases proportionally to the depth. And finally, by using a saturated solution of common salt, which is denser than water, we can show that at the same depth the bottom pressure is proportional to the density.

Fig. 63. Pressure on bottom is independent of the shape of the vessel. (Pascal's vases.)

68. Upward pressure of liquids. If one tries to push a pail under water bottom downward, one finds that considerable resistance must be overcome because of the upward push of the water on the bottom of the pail. To see just how much this upward push of the water is, let us try the following experiment.

As shown in figure 64, close with a glass plate or piece of cardboard, held in place by a thread, a glass cylinder which has its bottom edge ground off smooth. When we push this cylinder into a jar of water, we may let go the thread, and yet the glass bottom will not fall off. It is evident that there is an upward pressure due to the water. If we slowly pour colored water into the cylinder, the plate stays in

Fig. 64. Water presses upward as much as it presses downward.

place until the levels inside and outside are the same; then it falls off.

In general, *the upward pressure exerted by a liquid at any depth is equal to the downward pressure which would be exerted by the same liquid at the same depth.*

59. Liquids also exert pressure sidewise. We all know that if a hole is bored in the side of a tank or barrel of water, the water will spurt out. This means that before the hole was bored the liquid must have been pressing against that bit of the side of the barrel. Liquids, then, exert a sidewise pressure due to their weight, as well as a downward pressure.

We can investigate how this sidewise pressure varies with the depth by means of the gauge shown in figure 65. It consists of a rubber diaphragm *D*, which may be turned about a horizontal axis, and is connected by a rubber tube to a horizontal glass tube containing a globule *B* of some colored liquid. As we lower the pressure gauge into the jar of water, we observe that the globule moves to the right, showing a gradual increase of pressure with increase of depth. If we repeat this with the diaphragm facing in another direction, we get the same result. If we hold the frame at some fixed depth, and rotate the diaphragm around a horizontal axis, we find that the globule remains practically stationary, showing that the pressure is the same in all directions.

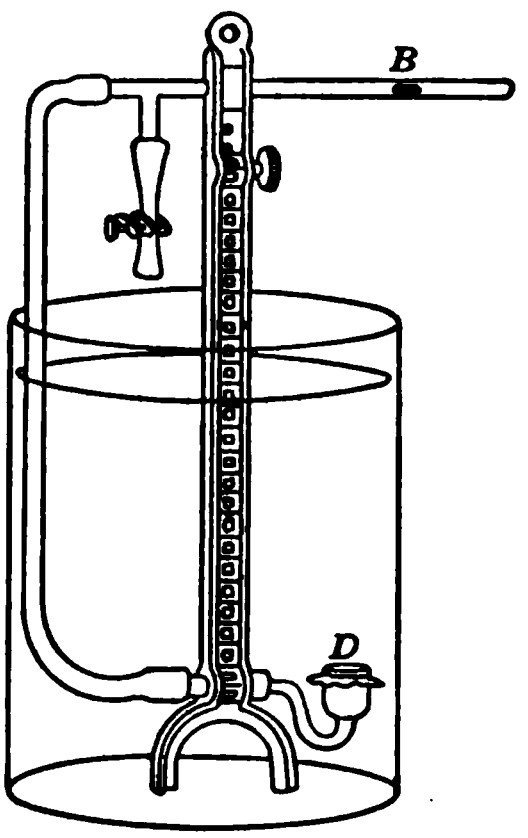

Fig. 65. Pressure gauge shows that pressure in a liquid is equal in all directions.

The sidewise pressure of a liquid increases with the depth and density of the liquid. At a given depth a liquid exerts in all directions exactly the same pressure.

60. Calculation of sidewise force. To calculate the total push of water against a dike or dam, we have to remember that the sidewise pressure increases gradually from zero at the surface to its maximum value at the bottom. We have already seen that at the bottom the pressure is equal to the weight

of a column of water with a base one unit square and with a height equal to the depth. The average sidewise pressure is equal to the pressure halfway down, or one half the bottom pressure. And, as always,

Force = area × average pressure.

FOR EXAMPLE, suppose we have a box 10 centimeters wide, 20 centimeters long, and 15 centimeters deep filled with water (Fig. 66). What is the *total force* tending to push out the *end* of the box? The pressure at a point halfway down the side would be 7.5 grams per square centimeter. There are in the end 10 × 15, or 150 square centimeters. Therefore the total force against the end is 150 × 7.5, or 1125 grams.

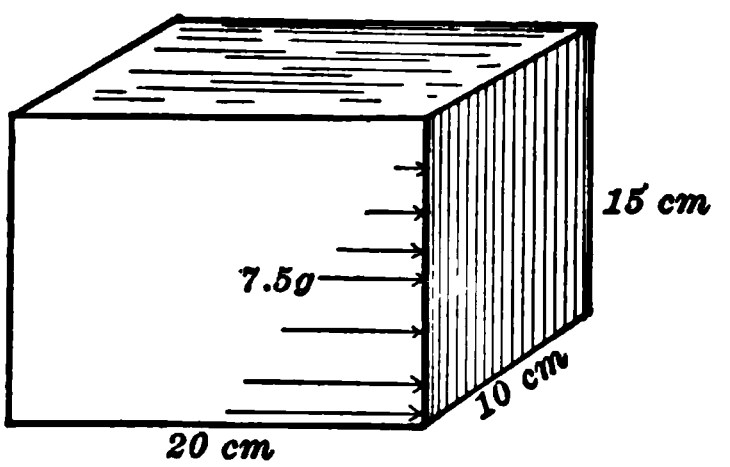

Fig. 66. Sidewise push of water against end of box is equal to area times average pressure.

Again, suppose the box were a large tank full of water, and the dimensions, expressed in feet, were 10 by 20 by 15. What is the end thrust? The pressure halfway down would be the weight of a column of water with 1 square foot for its base and 7.5 feet high, namely, 7.5 × 62.4, or 468 pounds per square foot. Since there are 10 × 15, or 150 square feet in the end of the tank, the total end thrust is 150 × 468, or 70,200 pounds, or about 35 tons.

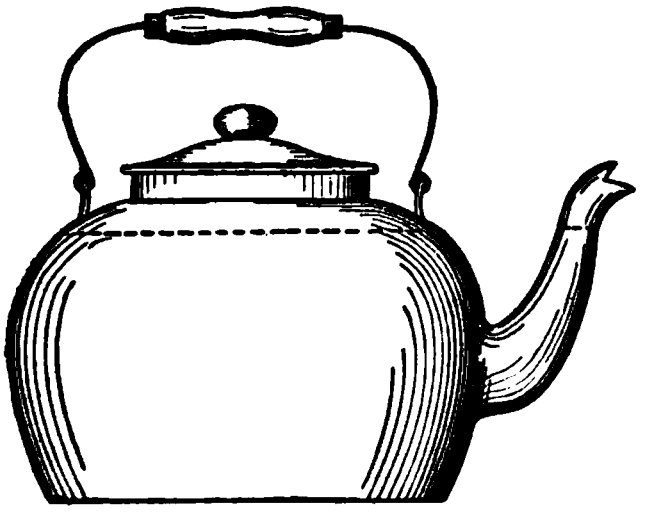

Fig. 67. Water seeks its own level in a teakettle.

61. Levels of liquids in connecting vessels. Probably everyone has observed that water stands at the same level in the spout of a teakettle as in the kettle itself (Fig. 67). That is, **liquids seek their own level**; or, the same liquid in any number of connecting vessels will have its free surface at the same level in each. This is to be expected from the fact that the pressure in a liquid depends upon the depth below the free surface. Thus if any

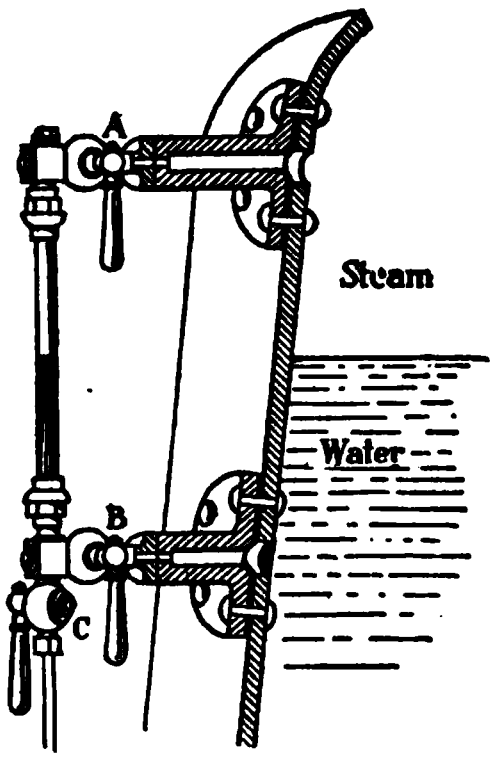

Fig. 68. Water gauge on a boiler.

point in the connecting portion between the two vessels were unequally far below the two surfaces, the pressures in either direction would not balance, and the liquid would flow from one vessel to the other until the levels were equalized.

The water gauge on a steam boiler (Fig. 68) is a good application of this principle. The gauge consists of a thick-walled glass tube which connects at the top with the steam space, and at the bottom with the water in the boiler. The valves *A* and *B* are closed when the glass tube is to be replaced. The valve *C* is opened occasionally to blow out the connecting passage, which sometimes clogs up.

PROBLEMS

1. The water in a standpipe is 10 meters deep. What is the pressure (g./cm.^{2}) on the bottom?

2. The water in a standpipe is 40 feet deep. What is the pressure (lbs./sq. in.) on the bottom?

3. If the diameter of the tank in problem 2 is 10 feet, what is the total force in tons which the bottom of the tank must sustain?

4. A diver goes down into sea water (density 1.03 grams per cubic centimeter) to a depth of 10 meters. What is the pressure on him in kilograms per square centimeter?

5. The hydraulic engineer speaks of pressure as "head of water," which means the pressure due to the weight of a column of water as high as the "head of water." Express in pounds per square inch a "head of 50 feet."

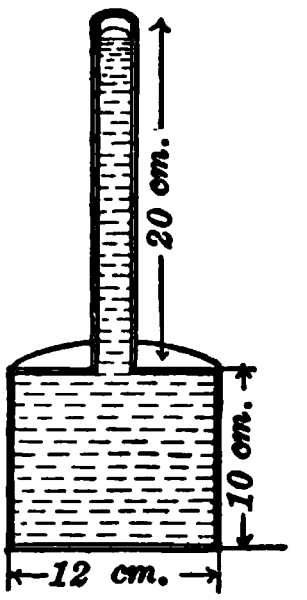

Fig. 69. Cylindrical can and tube full of water.

6. What is the pressure, near the keel, on a vessel drawing 6 meters in sea water?

7. Figure 69 is a cylindrical can 10 × 12 centimeters; out of the top rises a tube 20 centimeters long and 1 square centimeter in cross section. The box and tube are filled with water.

(*a*) Find the pressure (grams per square centimeter) on the bottom of the tank. Find the total force on the bottom.

(*b*) Does the size of the tube affect the pressure on the bottom?

(*c*) Find the pressure halfway up the side of the can. Find the total force against the cylindrical surface of the can.

(*d*) Find the pressure at the top of the can. Find the total upward force against the top.

(*e*) What is the total weight of water in can and tube?

(*f*) If the can and tube when empty weigh 250 grams, how much force will be required to support the can and tube when they are filled with water? (Compare this answer with the answers to part (*a*)).

8. A rectangular tank is 10 feet long, 5 feet wide, and 4 feet deep. Calculate the total force exerted on the end when the tank is full of water.

9. A cubic inch of mercury weighs 0.49 pounds. (*a*) Find the pressure on the bottom of a tumbler in which the mercury stands 4 inches deep. (*b*) If the tumbler is 2 inches in diameter, what is the total force on the bottom?

10. How high a column of water could be supported by a pressure of 1 kilogram per square centimeter?

11. The density of mercury is 13.6 grams per cubic centimeter. What is the pressure exerted at the base of a column 76 centimeters high?

12. A dam is 50 feet long and 6 feet high, and the water just reaches the top. What is the total force against the dam?

13. A hole 6 inches square is cut in the bottom of a boat drawing 10 feet in fresh water. What force must be exerted in order to hold a board tightly against the inside of the hole?

14. How much "head of water" is needed to give a pressure of 1 pound per square inch?

15. What must be the difference in height between a fire hydrant and the surface of the water in a city reservoir to give a pressure of 50 pounds per square inch at the hydrant?

16. The bottom of a tin pail is 16 centimeters in diameter and the top is 24 centimeters in diameter. Suppose the pail is filled with water to a depth of 25 centimeters. (*a*) What is the pressure on the bottom? (*b*) What is the whole force on the bottom?

62. Pressure transmitted by a liquid. Thus far we have been considering the pressure at various depths below the

surface of a liquid in an open vessel. Let us take now the case of a completely confined liquid.

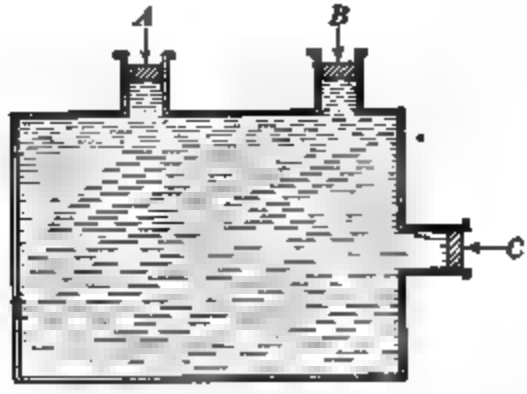

Fig. 70. Box filled with water and fitted with three equal pistons.

FOR EXAMPLE, the box in figure 70 is completely filled with water and is fitted with two equal pistons A and B. Any external force exerted on A will be transmitted by the water undiminished to B. If there is a third equal piston C in the side of the box, the same force will be transmitted undiminished to C, in addition to the push on C which is due to its depth.

Any external force exerted on a unit area of a confined liquid is transmitted undiminished to every unit area of the interior of the containing vessel. This fact was first stated by the French mathematician, Pascal (Fig. 71).

63. The hydraulic press. The most useful application of this principle can be described in Pascal's own words: "If a vessel full of water, closed in all parts, has two openings, of which the one is a hundred times the other, placing in each a piston which fits it, the man pushing the small piston will equal the force of a hundred men who push that which is a hundred times as large, and surpass that of ninety-nine. Whatever proportion these openings have, and whatever direction the pistons have, if

Fig. 71. Blaise Pascal (1623–1662). Famous French scientist and mathematician.

the forces that apply on the pistons are as the openings, they will be in equilibrium."

Suppose there is a force of 1 pound pushing down on the small piston (Fig. 72), and that the large piston has 100 times as great an area. It will be seen that the *pressure* on the large piston is 1 pound on each square inch, just as on the small piston. Then there must be 100 pounds pushing down on the large piston to balance it.

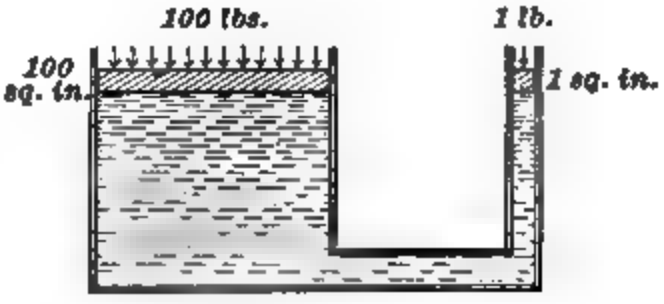

Fig. 72. Diagram of hydraulic press. Forces vary as areas of pistons.

In other words, the pressure is transmitted by the liquid so as to act with the same force on every square inch, and the *forces exerted on the two pistons are directly as their areas*.

64. Applications of the hydraulic press. This device of Pascal gives us an easy way of exerting enormous forces, such as are needed in pressing books into shape in book-binderies, in baling paper and cotton, in pressing sheet steel into shape for automobile mud guards, in extracting oil out of seeds, etc. The commercial machine (Fig. 73) is exactly like that described by Pascal except that there is usually a check valve v between the small piston and the big one, and the small piston is arranged to work like a pump, with a valve d at the bottom for admitting more oil. Often the small piston is forced down by a lever.

Fig. 73. Cross section of a hydraulic press.

The method of operation is simple. On the upstroke of the pump piston, the valve at the bottom of the pump opens, and oil flows in from the reservoir. On the downstroke of the pump piston, the oil is forced over through the connecting pipe past the valve, and pushes the large working piston up very slightly. If the large piston is 100

times as large in cross section as the small piston (diameters as 10 : 1), the large piston is lifted only $\frac{1}{100}$ the distance the pump piston is pushed down at each stroke. But since the force exerted by the large piston is, if we neglect friction, 100 times that applied to the small piston, it follows that the work done *on* the machine is equal to the work done *by* the machine. In the actual case the output is less than the input by the amount of work done against friction.

Pascal's principle is also used in the hydraulic elevators which are commonly employed in buildings where heavy loads are to be lifted.

Fig. 74. Hydraulic chair with cross section of base.

The **hydraulic jack** is a very compact machine for lifting heavy weights, from 50 to 600 tons, through short distances up to 1 foot. Perhaps the most familiar use of this principle is found in the hydraulic chair used by dentists and barbers (Fig. 74). Explain its working.

PROBLEMS

1. If the diameters of two pistons in a hydraulic press are 1 inch and 10 inches, what are their areas of cross section?

2. If the small piston in problem 1 is subjected to a pressure of 10 pounds per square inch, what pressure must be applied to the large piston to hold it in place? Neglect friction.

3. If a total force of 10 pounds is applied to the small piston in problem 1, what total force must be applied to the large piston to hold it in place?

4. The diameters of the pistons in a hydraulic press are 20 inches and 1 inch. What must be the force on the small piston if a force of 5 tons is to be exerted by the large piston?

5. In problem 4, suppose the small piston to move 1 foot. How far does the large piston move?

6. The water pressure in a city water main is 50 pounds per square inch and the diameter of the plunger of an elevator is 10 inches. (*a*) Neglecting friction, compute how heavy a load the elevator can lift? (*b*) If the friction loss is 25%, what load can be lifted?

7. In the little working model of a hydraulic press shown in figure 75, the large piston is 1 inch in diameter and the small piston is 0.25 inches in diameter. The small piston is worked by a lever and is attached at a point 2 inches from the fulcrum. If a force of 20 pounds is applied at a point 10 inches from the fulcrum, what force is exerted by the large piston?

Fig. 75. Working model of a hydraulic press.

Fig. 76. The man lifts his own weight by pouring in water.

8. A man weighing 150 pounds stands on the upper board *C* of a hydrostatic bellows (Fig. 76) and pours water into the tube to lift his own weight. If the board is 1 foot square, how high will the water stand in the tube above that in the bellows to balance his weight?

Practical Exercises

1. Construction of dams. Study the cross section of some large dams and explain the shape. Why are some dams curved with the convex side upstream?

2. Construction of water tanks. What is the method used to get greater strength at the bottom?

65. Buoyant effect of liquids. When we are swimming, our bodies are very nearly floated by the water. When we lift a stone from the stream bed, we find that it becomes heavier on emerging from the water. Things seem to be lighter under water; in other words, water buoys up anything placed in it.

In order to find how much lighter an object is under water than it is out of water, let us try the following experiment.

We have a hollow metal cylindrical cup C, and a cylindrical block B, which has been nicely turned to fit inside the cup C. We hang both from a beam balance, as shown in figure 77, and counterbalance with a weight W on the other scalepan. Then we bring a glass of water up under the block B, so that it is entirely under water. The left-hand side of the balances rises, which shows the upward push of the water upon B. But we can restore the equilibrium again by pouring water into the cup C until it is just filled. This shows that *B loses in apparent weight the weight of its own bulk of water*. If we try the experiment, using kerosene instead of water, we find that exactly the same thing is true.

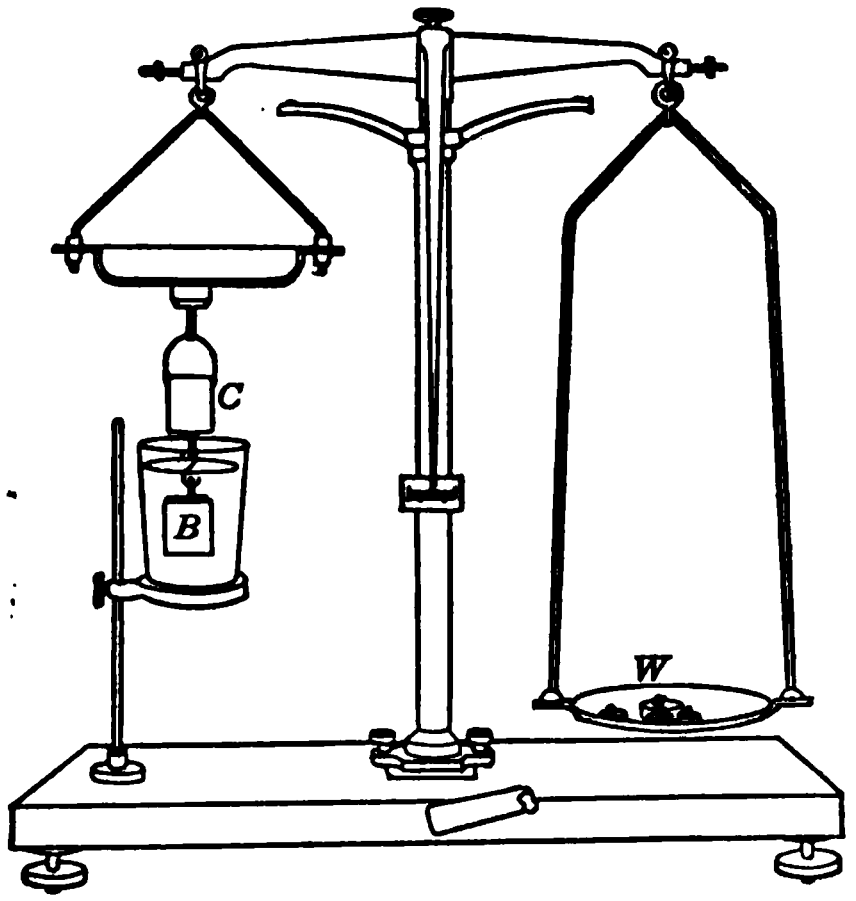

Fig. 77. Buoyant effect of liquids is equal to weight of liquid displaced.

66. Archimedes' principle. The principle proved by this experiment may be stated as follows:

The loss of weight of a body submerged in a liquid is the weight of the displaced liquid.

It is supposed that this principle about the loss of weight of a body in a liquid was discovered about 250 B.C. by the old Greek philosopher Archimedes. Hiero, king of Syracuse, suspected a goldsmith who had made a crown for him, and ordered Archimedes to find out if any silver had been mixed with the gold in the crown. To do this without destroying the crown seemed a puzzle at first, but one day, while Archimedes was in the public bath, he noticed that his body was buoyed up by the water in which it was submerged. Seeing in this effect the solution of his problem, he leaped from the

bath and rushed home shouting, "Eureka! Eureka!" (I have found it! I have found it!)

67. Explanation of Archimedes' principle. This principle will be readily understood from the following example.

Suppose we place a rectangular block in a jar of water, as shown in figure 78. Let the block be $10 \times 6 \times 4$ centimeters, and let the top be 5 centimeters below the surface of the water, and the bottom 15 centimeters beneath the surface. Then the pressure on top, that is, the downward push on each square centimeter, is 5 grams, and the pressure on the bottom, that is, the upward push on each square centimeter, is 15 grams. Since the top and bottom each have an area of 6×4, or 24 square centimeters, the whole upward push on the bottom is 24×15, or 360 grams, while the whole downward push on the top is only 24×5, or 120 grams. This leaves a net upward force, or buoyancy, of 240 grams. But this is exactly the weight of the displaced water, for the volume of the displaced water is $10 \times 6 \times 4 = 240$ cubic centimeters, and we have seen in section 12 that this amount of water weighs 240 grams.

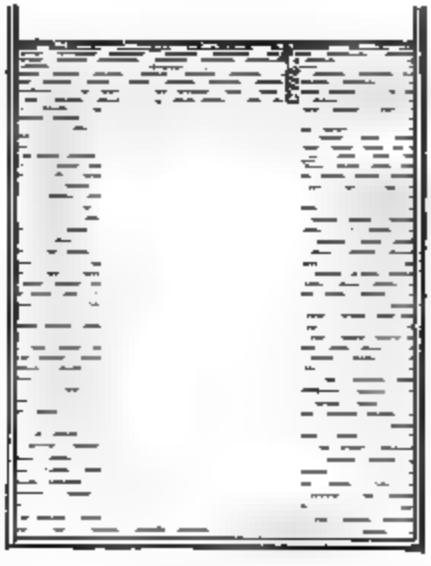

Fig. 78. Lifting effect of water on submerged block.

The same sort of reasoning would hold at any depth and for any liquid other than water and with any irregularly shaped body. So it may be said that in any liquid of any density a body seems lighter by the weight of the displaced volume of *that liquid.*

68. Floating bodies. What happens when this upward force, or buoyant force, is more than the weight of the body submerged? Evidently the body rises and continues to rise as long as the upward push remains greater than the downward pull of gravity. But as soon as any of the body projects above the surface, less water is displaced and the upward push is less. When enough of the body projects to reduce the buoyant force to equality with the weight, the body stops

rising and floats. In this case we see that the loss of weight is the whole weight itself.

A floating body displaces its own weight of the liquid in which it is floating.

The following experiment will help to make this principle of Archimedes, as applied to floating bodies, seem more real. Suppose we balance an overflow can on a platform scale, as shown in figure 79. The can is filled to overflowing with water and is balanced by the weights on the other platform. We place a dish to catch any more water that

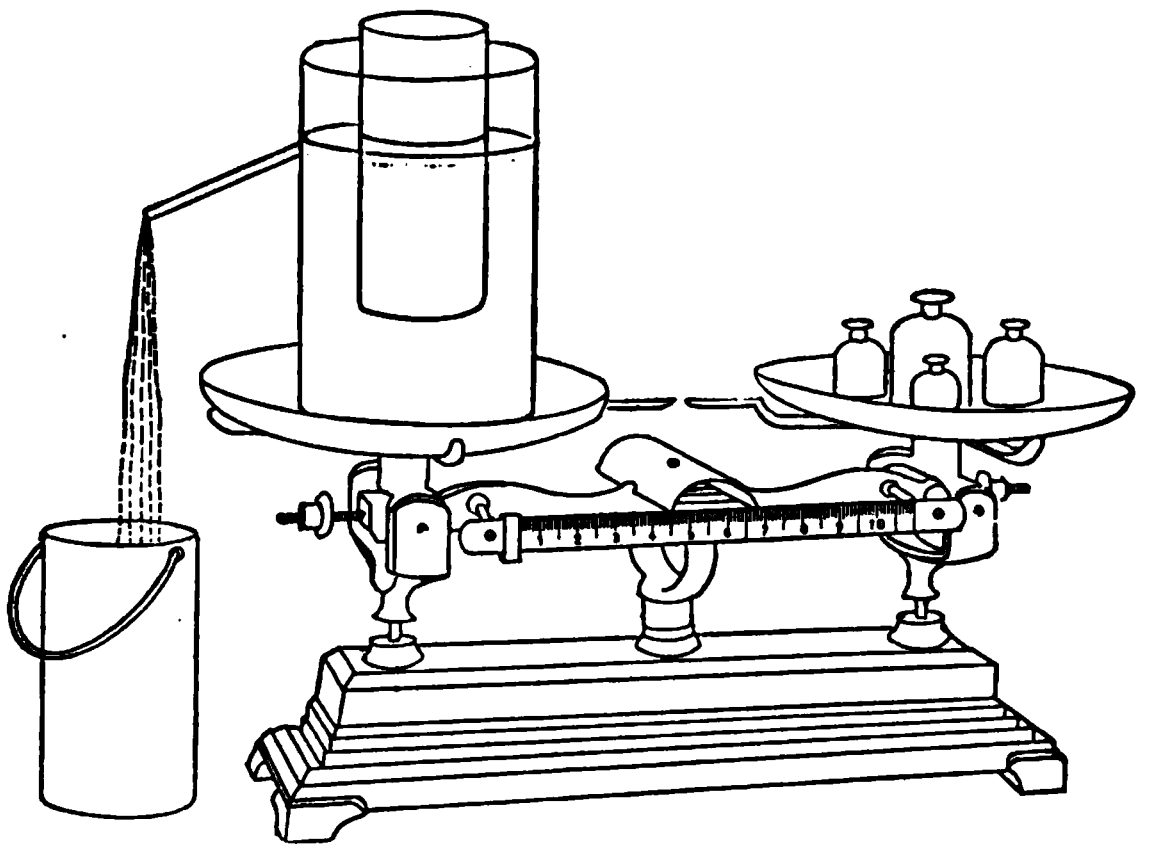

Fig. 79. Floating body displaces its own weight of liquid.

overflows, and then put a block of wood gently into the can. After the water has stopped overflowing, it will be seen that the scales again balance. This means that the weight of water which flowed over was just equal to the weight of the block. This can be verified in another way by weighing the water displaced by the block and caught in the dish.

69. Applications of Archimedes' principle. If we know the total weight of a ship and its equipment, we can tell at once what weight of water it will displace, and so it is possible to compute how deep it must sink to displace its own weight of water. It is also evident that a boat must sink a little deeper in fresh water than in salt water, and will sink deeper when loaded than when empty.

A submarine boat (Fig. 80) is so constructed that it is only slightly lighter than water. It can be submerged by letting water into the

Fig. 80. Submarine floats or is submerged by varying its displacement.

ballast tanks and can be made to rise again by forcing compressed air into the ballast tanks and thus driving the water out of them.

The same principle is applied in the floating drydock shown in figure 81. When the tanks T, T, T are full of water, the dock sinks until the water level is at LL. The ship to be repaired is then floated into the dock and the water is pumped out of the tanks T, T, T. As the compartments are emptied of water, the dock rises until the water level is at the line WW, lifting the ship out of water. The ship and dry-dock still displace their own weight of water, but the displacement is in a different place.

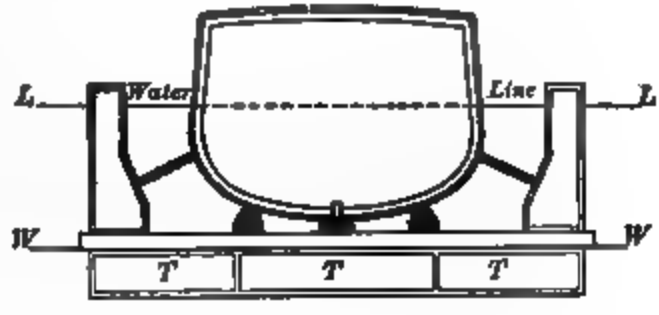

Fig. 81. Cross section of floating drydock.

PROBLEMS

1. A piece of stone weighing 235 grams in air and 128 grams in water is put into a dish just full of water. How much water runs over?

2. A rowboat weighs 200 pounds. How many cubic feet of water does it displace?

3. If a ferryboat weighs 800 tons, what volume of sea water will it displace after it takes on board a train weighing 600 tons?

4. What is the volume of a 125-pound boy if he can float entirely submerged except his nose?

5. A barge is 20 feet long and 10 feet wide, and has vertical sides. When an automobile weighing 4000 pounds is driven on board, how much deeper in the water does the boat sink?

6. A rectangular block is 22 centimeters long, 6 centimeters wide, and 4 centimeters high, and floats in water with 1 centimeter of its height above water. How much does it weigh?

7. A cube 5 centimeters on an edge weighs 600 grams in air. How much does it weigh in water?

8. How much will a 10-centimeter cube of brass (density 8.4 grams per cubic centimeter) weigh in gasoline (density 0.75 grams per cubic centimeter)?

9. A rectangular solid $10 \times 8 \times 6$ centimeters is submerged in water so that the top, whose dimensions are 10×8 centimeters, is horizontal and 12 centimeters below the water surface.

(*a*) Find the total force pressing down on the top.
(*b*) Find the total force pushing up on the bottom.
(*c*) Find the loss of weight of the solid.

10. A river barge 60 feet long and 20 feet wide floats 5 feet out of water when empty. It is loaded with coal until the top of the barge is only 1 foot out of water. How many long tons (2240 lbs.) of coal were in the load?

PRACTICAL EXERCISES

1. Floating docks and bridges. How are the pontoons constructed? How are they anchored? What determines how much they can carry?

2. Life preserver. How much effort is required to keep the average person afloat in fresh water? Why does this depend on how much of the body is kept under water? Determine the lifting effect of a standard life preserver when entirely submerged. What part of an average person's body would be kept above water by a standard life preserver? (See *Packard's* Everyday Physics, Ginn & Co.)

70. Specific gravity and density. Archimedes' principle furnishes us with a convenient method of comparing the weight of a substance with the weight of an equal bulk of water. The ratio of these weights is called the *specific gravity* of the body. In other words,

$$\text{Specific gravity} = \frac{\text{weight of body}}{\text{weight of equal bulk of water}}.$$

FOR EXAMPLE, a piece of marble weighs 100 grams and an equal bulk of water weighs 40 grams; then the marble is $100/40 = 2.5$ times as heavy as the water. The specific gravity of marble, then, is 2.5.

The term **specific gravity** does not mean quite the same thing as **density.** The specific gravity of a substance is an *abstract* number; for example, the specific gravity of mercury is 13.6. But the density of a substance is a *concrete* number; for example, the density of mercury is 13.6 grams per cubic centimeter, or 850 pounds per cubic foot.

In the metric system the density of water is one gram per cubic centimeter, and therefore

Density (g. per cm.^{3}) = (numerically) specific gravity.

In the English system the density of water is 62.4 pounds per cubic foot, and therefore

Density (lbs. per cu. ft.) = (numerically) 62.4 × specific gravity.

71. Methods of determining specific gravity of solids. GENERAL RULE. *First weigh the object. Next find by some indirect method the weight of an equal bulk of water. Finally divide the weight of the object by the weight of the equal bulk of water.*

This general statement covers all the various processes for finding the specific gravity either of solids or of liquids. The different procedures vary only in the method of finding the weight of an equal bulk of water.

1st Method. If the object is a **regular geometrical solid**, one can measure its dimensions and **calculate its volume**, and from that get the weight of an equal bulk of water.

2d Method. If the object is a solid that will **sink in water** and will not dissolve, one can determine its **apparent loss of weight in water.** This is the weight of an equal bulk of water. That is,

$$\text{Specific gravity} = \frac{\text{weight of body}}{\text{loss of weight in water}}.$$

FOR EXAMPLE, suppose a piece of copper weighs 178 grams in air and 158 grams in water. The loss, 20 grams, is the weight of an equal bulk of water. Therefore the specific gravity of copper = 178/20 = 8.9.

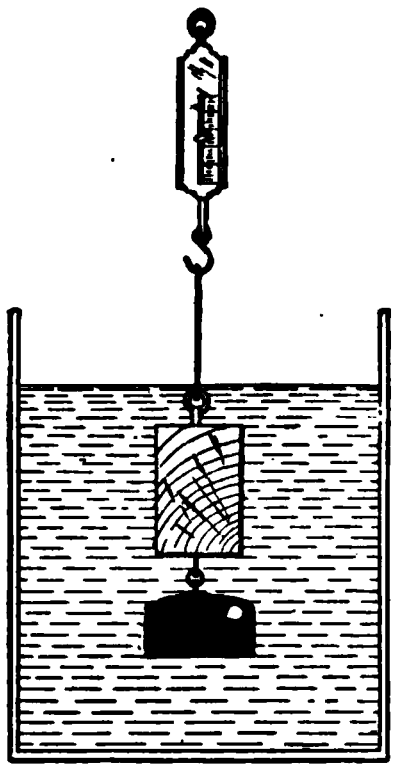

Fig. 82. Specific gravity with sinker.

3d Method. If the object is **lighter than water** and does not dissolve, select a sufficiently large **sinker** and suspend it below the object, as shown in figure 82. Then bring a jar of water up under the whole thing until the water level is between the sinker and the object, and weigh. Then raise the jar still farther until the water level is above the object, and weigh again. This weight will be less than the first because in this case the water buoys up the object, while in the first case it does not. The difference between the two weights is equal to the weight of the water displaced by the object.

$$\text{Specific gravity} = \frac{\text{weight of body}}{\text{lifting effect of water on body only}}.$$

For example, suppose a piece of wood weighs 120 grams in air, and that the wood and a suitable sinker weigh 270 grams when the sinker is under water, and 90 grams when both are under water. Then the lifting effect of the water on the wood is 270−90, or 180 grams. Therefore the specific gravity of the wood is 120/180 = 0.667.

Notice that the loss of weight, or the lifting effect of the water, is larger than the whole weight. This is why the body floats.

72. Specific gravity of liquids.

1st Method. Weigh a **bottle** empty, then full of the liquid, and then full of water. Subtract the weight of the empty bottle in each case, and then compare the weight of the liquid with the weight of an equal volume of water.

$$\text{Specific gravity} = \frac{\text{weight of liquid}}{\text{weight of equal volume of water}}.$$

For example, a bottle weighs 400 grams when empty and perfectly dry, 900 grams when full of water, and 775 grams when full of gasoline. Then the specific gravity of gasoline is $\frac{375}{500} = 0.75$.

Bottles, called **specific-gravity flasks** (Fig. 83), are made for the purpose of determining the specific gravity of liquids with great accuracy and facility. They are usually made to contain a definite quantity of pure water at a specified temperature, such as 500 grams, when filled to a mark on the neck.

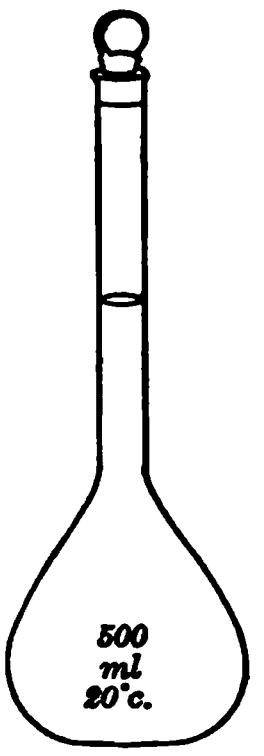

Fig. 83. Specific-gravity flask.

2d Method. Weigh a piece of glass in air, then in the liquid, and then in water. Find the **loss of weight in the liquid** and the **loss of weight in water.** This loss of weight in the liquid is the weight of the liquid displaced, and the loss of weight in water is the weight of an equal volume of water. Then

$$\text{Specific gravity} = \frac{\text{loss of weight in liquid}}{\text{loss of weight in water}}.$$

FOR EXAMPLE, suppose the glass weighs 330 grams in air, 150 grams in sulfuric acid, and 230 grams in water. The glass loses 180 grams in acid and 100 grams in water. Since these are the weights of equal volumes of acid and water, the specific gravity of the acid = 180/100 = 1.8.

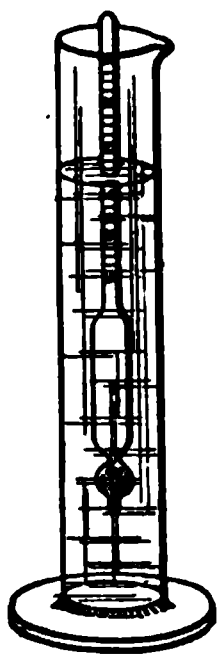

Fig. 84. Hydrometer used to measure specific gravity of liquids.

*3d Method.** The most common way of determining the specific gravity of liquids is by the **hydrometer.** This is usually made of glass, and consists of a cylindrical stem and a bulb weighted with mercury or shot to make it float upright (Fig. 84). The liquid is poured into a tall jar, and the hydrometer is gently lowered into the liquid until it floats freely. The point where the surface of the liquid touches the stem of the hydrometer is noted. There is usually a paper scale inside the stem, so made that the

* There is another method, using balancing columns, which will be described in the Laboratory Manual. To understand it one must have read Chapter IV.

specific gravity (or density in grams per cubic centimeter) can be read off directly. In light liquids, like kerosene, gasoline, and alcohol, the hydrometer must sink deeper to displace its weight of liquid than in heavy liquids like brine, milk, and acids. In fact, it is usual to have two separate instruments, one for heavy liquids, on which the mark 1.000 for water is near the top, and one for light liquids, on which the mark 1.000 is near the bottom of the stem.

73. Commercial uses of the hydrometer. Since the commercial value of many liquids, such as sugar solutions, sulfuric acid, alcohol, and the like, depends directly on the specific gravity, there is extensive use for hydrometers. Perhaps the best-known form of hydrometer is the kind used in testing milk, called a **lactometer.** The specific gravity of cow's milk varies from 1.027 to 1.035. Since only the last two figures are important, the scale of a lactometer is made to run from 20 to 40, which means from 1.020 to 1.040. The specific gravity of milk does not give a conclusive test as to its worth. In addition to water (which is about 87%), milk contains some substances which are heavier than water, such as albumin, sugar, and salt; and others that are lighter than water, such as butter fat. Besides the specific gravity, one needs to determine the amount of fat, and, if possible, of the other solids in the milk, in order to know its richness. Of course the most important question about milk is its cleanness, but this must be left to the bacteriologist.

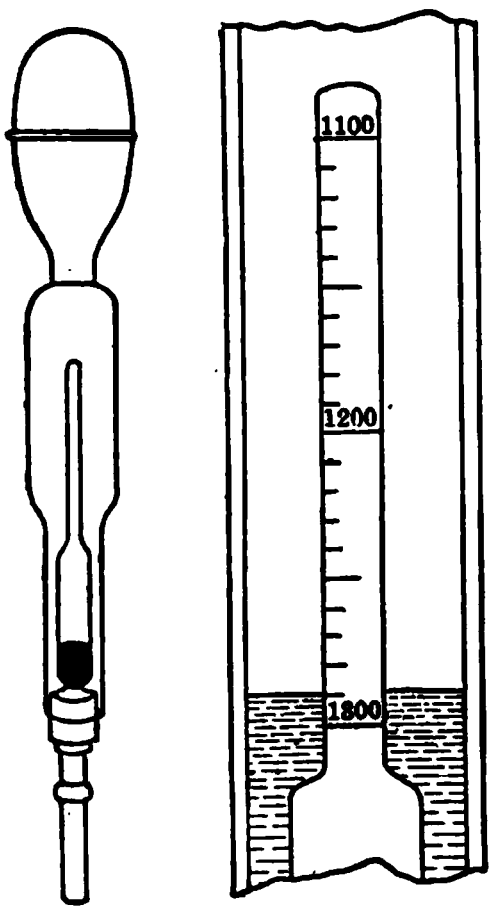

Fig. 85. Syringe hydrometer used to test storage batteries.

Another very common use of the hydrometer is in testing the ordinary lead-plate **storage battery.** In section 326 we shall learn that the liquid in this battery is dilute sulfuric acid, and that the condition of the battery as to charge and discharge is best determined by measuring the density of this acid. When the battery is fully charged, the solution should have a specific gravity of about 1.29, and as the battery discharges the specific gravity drops to about 1.15. In testing the automobile storage battery, the hydrometer is made small and inclosed in a

large glass tube (Fig. 85). To get a sample of the acid, the bulb at the top of the large glass tube is squeezed and then released, thus drawing up liquid enough to float the hydrometer.

QUESTIONS AND PROBLEMS

1. A piece of ore weighs 42 grams in air and 25 grams in water. Calculate its specific gravity.

2. A stone weighs 15 pounds in air and 9 pounds in water.

(*a*) Find its specific gravity.

(*b*) Find its density in the metric system.

(*c*) Find its density in the English system.

3. A body has a specific gravity of 3.5. What is its density in (*a*) the metric system, and (*b*) the English system?

4. Which has the greater specific gravity, whole milk or skim milk? Why?

5. Which has the greater specific gravity, pure milk or watered milk? Why?

6. If the specific gravity of lead is 11.4, how many cubic centimeters of lead does it take to make a kilogram weight?

7. If the specific gravity of cork is 0.25, how many cubic feet of cork are there in 1 pound of cork?

8. A block of wood, $15 \times 10 \times 8$ centimeters, floats with one of its largest faces 2 centimeters out of water.

(*a*) Find its weight.

(*b*) Find its specific gravity.

9. A plank 8 centimeters thick floats with 5 centimeters under water. Find its specific gravity.

10. A boy is carrying a 40-pound pail of water in one hand and a 2-pound trout in the other. The specific gravity of the trout is 1. He puts the trout into the pail of water. (*a*) What is the "loss of weight" of the trout? (*b*) How much does the boy have to lift?

11. A block of wood weighs 150 grams; a sinker is suspended from it, and when the sinker is under water and the block is in air, the combination weighs 350 grams. When the wood and the sinker are both under water, they weigh 100 grams. Find (*a*) the volume of the block of wood, and (*b*) its specific gravity.

12. If a boy can lift a 90-pound stone on dry land, how heavy a stone can he raise from the bottom of a swimming hole? Assume the specific gravity of the stone to be 2.5.

13. A cube of iron 10 centimeters on an edge (specific gravity 7.5) floats in mercury (specific gravity 13.6). How many cubic centimeters are above the mercury?

14. A can weighs 190 grams when empty, 600 grams when full of water, and 613 grams when full of milk.

(*a*) What is the capacity of the can in cubic centimeters?

(*b*) What is the specific gravity of the milk?

15. How much does 1 cubic centimeter of lead (specific gravity 11.4) weigh in kerosene (specific gravity 0.79)?

16. A bottle weighs 80 grams when empty, 280 grams when filled with water, and 250 grams when filled with a medicine. What is the specific gravity of the medicine?

17. An empty bottle weighs 50 grams; the same bottle full of water weighs 200 grams. Some dry sand is put into the empty bottle and it then weighs 320 grams. Finally the bottle is again filled with water, and the bottle, sand, and water weigh 370 grams.

(*a*) Find the capacity of the bottle.

(*b*) Find the volume of the sand.

(*c*) Find the specific gravity of the dry sand.

18. If one buys 10 pounds of mercury (specific gravity 13.6), how many cubic inches should one get?

19. If the inside of an ice chest measures 24 × 18 × 12 inches, how many pounds of ice (specific gravity 0.92) will it hold?

20. How many pounds of sulfuric acid (specific gravity 1.84) does a 5-gallon carboy contain?

PRACTICAL EXERCISE

Making a hydrometer. Use a test tube with a one-hole rubber stopper carrying a thin-walled glass tube. Ballast the test tube with lead shot. How can you make such a hydrometer indicate directly specific gravity?

74. City waterworks. Every city has to face the problem of providing a plentiful supply of pure water for household use, for industrial purposes, and for fire protection. Not only must there be enough water, but it must be furnished at sufficient pressure to force it to the tops of high buildings. If the city is located near the mountains, as are Denver and Los Angeles, it is an easy matter to conduct the water from

an elevated reservoir in large pipes or mains to the houses. Since the water tends to seek its own level, it will rise in the

Fig. 86. Cross section of a water system.

buildings to the height of the reservoir. But in most cities, such as New York, Philadelphia, and Boston, the *gravity system* of waterworks is impossible and a *pumping* system must be employed. This includes an extensive watershed sometimes at a long distance from the city, a holding reservoir, aqueducts, pumping stations, standpipes, and distributing mains (Fig. 86). The operation of the big steam pumps that are used will be explained later (section 194).

75. Faucets and hydrants. The only parts of this great system of water pipes which we ordinarily see are the fire hydrants on the edges of our sidewalks, and the taps or faucets at our sinks and bathtubs. Each is merely a valve for opening and closing a pipe.

The internal construction of the ordinary faucet is shown in figure 87. The handle operates a screw which forces a disk, faced with a fiber washer, against a circular opening, or seat, and so shuts off the water. If the handle is turned the other way, the disk is raised, leaving an opening. This sort of valve may get out of order in two ways: the washer may wear out or the packing about the handle rod may get loose. Both can easily be replaced. The packing consists of cotton twine wrapped around the valve stem, and is held in place by what is called a gland.

Fig. 87. Cross section of common faucet.

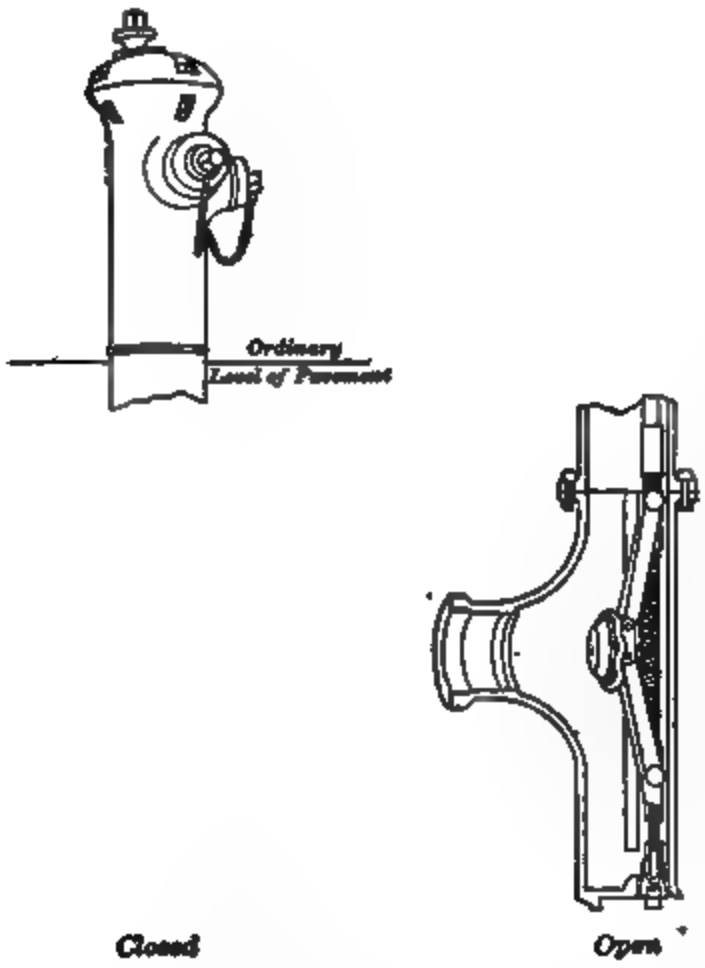

Fig. 88. Cross section of a fire hydrant with cut-off valve closed and open.

The internal construction of a hydrant is shown in figure 88. The fire hose is attached near the top of the hydrant. A wrench applied to a vertical rod opens the cut-off valve. To prevent water from standing in the hydrant and freezing in winter, there is an ingenious device which opens a drip valve at the bottom whenever the cut-off valve is closed.

76. How we measure water pressure. Doubtless we have all noticed that water flows more slowly from a faucet on an upper floor than on the first floor. This is because the water pressure is low there. To measure it, we use some form of **pressure gauge**. For small pressures we take an **open mercury manometer**, the most accurate form of pressure gauge. It consists of a U-shaped tube partly filled with mercury, as shown in figure 89.

Suppose the water pressure is enough to balance a mercury column 4 feet high. How much is the pressure in pounds per square inch? A column of mercury 4 feet high and 1 square inch at the base would contain 48 cubic inches, and would weigh 23.5 pounds. Therefore the pressure of the water would be 23.5 pounds per square inch. With such a gauge it is easy to show that the water pressure is less on the top floor than in the basement.

Fig. 89. Mercury pressure gauge.

A mercury gauge is so cumbersome and expensive that a **Bourdon spring gauge** is generally used. It consists of a brass tube of elliptical section, bent into a nearly complete ring and closed at one end, as shown in figure 90. The flatter sides of the tube form the inner and outer sides of the ring. The open end of the tube is connected with the pipe through which the liquid under pressure is admitted. The closed end of the tube is free to move. As the pressure increases, the tube tends to straighten out, moving a pointer to which it is connected by levers and small chains. These spring gauges have the scale so graduated that they read directly in pounds per square inch.

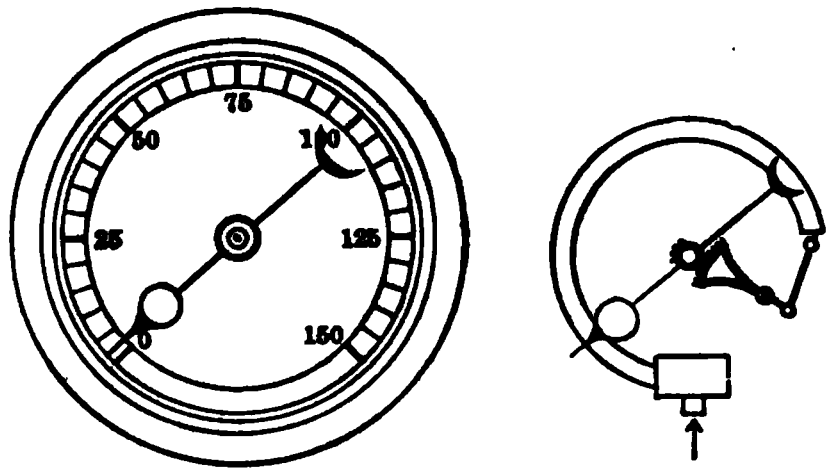

Fig. 90. Bourdon pressure gauge.

77. Fluctuations in water pressure. Not only does one find a decrease of water pressure in going from the basement to the attic of a house, but if the gauge is attached at one point and watched closely, it will be seen to fluctuate according as much or little water is being drawn elsewhere in the building.

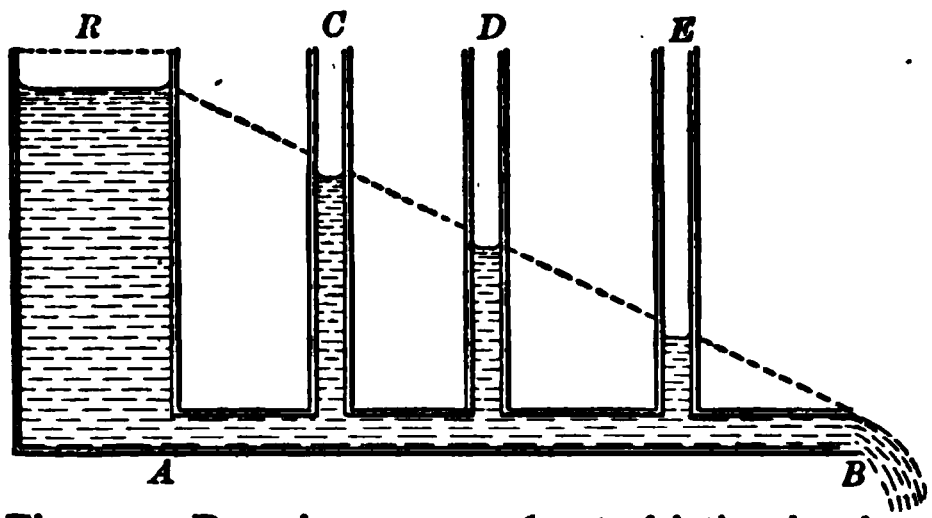

Fig. 91. Drop in pressure due to friction in pipe.

The following experiment shows the same thing on a smaller scale. The tank or reservoir *R* in figure 91 is connected with a supply pipe *AB*. The pressure along the pipe is indicated by the height of the water in the tubes *C*, *D*, and *E*. When the pipe is closed at *B*, the level is the same in *R*, *C*, *D*, and *E*; this is called the static condition. But when the stopper is removed from *B*, and water flows out, the pressure is no longer the same at all points along the pipe, but falls off as the distance from the reservoir *R*

increases. This drop in pressure is due to friction against the walls of the pipe through which the water has to run.

From this experiment we see that, when a number of faucets are open and the water is flowing, the pressure in the neighborhood becomes small. To equalize these changes in water pressure and also to provide some flexibility in the system, it is common to have a standpipe in the water system nearer the houses than the main reservoir. This also serves as an auxiliary reservoir in case of emergency.

78. A water meter. It is now customary to measure in cubic feet or in gallons the quantity of water which is used by each consumer. The water meter is located in the supply line and is usually in the basement where the pipe from the main enters the house.

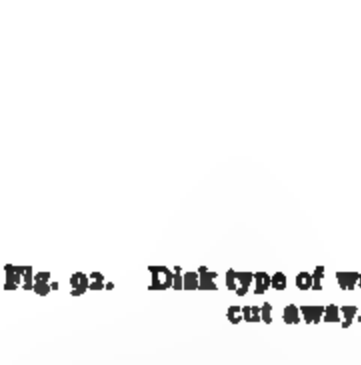

Fig. 92. Disk type of water meter, side cut away.

One of the commonest meters used for domestic purposes, the disk type, is illustrated in figure 92 with one side cut away to show the working parts. In the bottom is the measuring chamber, which contains a hard-rubber disk. This disk is attached at the center to a small sphere which works in sockets at the top and bottom of the chamber. The disk just touches the sides of the chamber all the way around, and also just touches the conical upper and lower faces of the chamber. As the water passes through the meter, it causes the disk to move with a rotary nodding motion (nutation), a certain quantity of water passing through the meter for each complete nutation of the disk. The end of the spindle projecting upward from the disk moves in a circular path and actuates the gears that drive the mechanical counter above.

The dial of a water meter is shown in figure 93. It consists of six circles, each divided into 10 divisions. The number on the outside of each circle indicates the number of cubic

feet for one complete revolution of the hand. Thus the dial in figure 93 indicates 94,450 cubic feet (the "one" circle not being read). An official of the water department reads the meter periodically, and by subtracting can easily compute the amount of water consumed during the period, and so fix the charge in proportion.

Fig. 93. Dial of water meter, reading 94,450 cu. ft.

79. Water wheels. Running and falling water have long been utilized as a source of power. Any community having a waterfall or a rapid in a near-by river has a valuable source of power. The older types of water wheels are the **overshot**, in which the weight of the water slowly turns the wheel, and the **undershot**, in which the wheel is let down into a swiftly flowing current. These older types of water wheels are almost as efficient as modern wheels, but the amount of power which even a large wheel can deliver is too small for most installations.

The modern forms of water wheels are the Pelton wheel and the turbine. The **Pelton** wheel is used when the supply of water is small but the pressure, or "head," is great. Frequently the water in a lake located high up on a mountain is brought down in strong steel pipes and allowed to rush with terrific velocity against the cup-shaped buckets on the rim of the wheel (Fig. 94).

Fig. 94. Pelton water wheel used for high heads.

Thus, at Big Creek, California, the reservoir is about 1900 feet above the wheels, the water comes through a 6-inch nozzle at a speed of 350 feet per second (about 3.5 miles per minute), and the water wheels are 94 inches in diameter and revolve at 375 r.p.m.

Fig. 95. Water motor attached to faucet.

We may illustrate this type of wheel by a little water motor (Fig. 95), which may be attached to an ordinary kitchen faucet and used to drive a small grinding wheel for sharpening knives, scissors, and carpenters' tools.

By far the most important type of water wheel to-day is the turbine. This is used where a large flow of water at a moderate "head" is available, as at Niagara Falls and at Keokuk, Iowa, on the Mississippi River. The turbine wheel (Fig. 97) is placed at the bottom of a cylindrical well, or pit, and is submerged in water to a depth equal to the height of the water supply. The water is let into the wheel case through *many inlets*, or passages, between shutters AA, which are so curved as to direct the water against the moving blades BB of the wheel in the most favorable direction to produce rotation. When the water has done its work, it falls from the bottom of the wheel case into the "tail race" below. The turbine is mounted on a vertical shaft, which transmits the power to the electric generator above. The amount of water which passes through a turbine is controlled by rotating the guide vanes so as to increase or decrease the size of the openings between the vanes.

The energy expended upon a water wheel is the product of the weight of water which passes through it by the head of water, or the difference in level between the reservoir and the tail race.

For example, the head at Niagara is 136 feet, and each turbine can handle about 22,500 cubic feet of water per minute. Then the energy expended in one minute upon each turbine is $22{,}500 \times 62.4 \times 136$, or 191,000,000 ft. lb. That is, the *input* is about 5800 horse power. Since the *output* is 5000 horse power, the efficiency is about 86%.

Fig. 96. Horizontal section of a turbine water wheel at Keokuk, Iowa, to show stationary and moving blades. The water for each turbine enters at four intakes, which converge into a scroll chamber so shaped that the water strikes every point on the circumference of the wheel with equal velocity.

Fig. 97. Vertical section of the above water turbine in position. Each turbine is direct-connected with an electric generator on a vertical shaft. There are at present fifteen such units, each with a capacity of 7500 kilowatts. The ultimate installation at Keokuk will have twice its present capacity.

The efficiency of modern water wheels (Fig. 98) of both types is frequently from 80 to 90 per cent.

Fig. 98. Various sizes of runners used in modern water wheels.

Questions and Problems

1. What is the mechanical construction of the interior of a self-closing faucet?

2. How would you detect by means of a water meter a leak in your household plumbing?

3. How would you find the cost of the water used in a garden hose for 1 hour?

4. If a schoolhouse uses 1750 cubic feet of water in one week and if water costs 25 cents per 1000 gallons, what is the weekly water bill?

5. The water level in a tank on top of a building is 100 feet above the ground. What is the pressure in pounds per square inch at a faucet 10 feet above the ground?

6. If 200 cubic feet of water flow each second over a dam 25 feet high, what is the available power? (Compute the power required to lift the water.)

7. If the efficiency of the water wheel used at the dam described in problem 6 is 65%, how many horse power can it supply?

8. How many cubic feet of water must be supplied every second to an overshot wheel which is 20 feet in diameter and delivers 40 horse power at an efficiency of 85%?

9. In the power plant of the city of Tacoma there is a turbine which uses 145 cubic feet of water per second at a head of 415 feet. If the efficiency is 90%, what is the horse power?

10. Compute the output in horse power of each of the Big Creek water wheels described on page 88, assuming that each wheel is fed by one nozzle, and that the efficiency is 80%.

11. The power plant at Wallis (Switzerland) utilizes a fall of 1650 meters (said to be the highest in the world). The Pelton wheel develops 3000 horse power. If the efficiency is 80%, how many kilograms of water flow out every second? (1 horse power = 76 kilogram-meters per second.)

PRACTICAL EXERCISE

Power and efficiency of a water motor. Attach the motor to a faucet and measure the water pressure while the motor is running. Make a brake test by using two spring balances with a heavy cord around a pulley. Calculate the horse power and efficiency under widely varying loads. (For details, see *Good's* Laboratory Projects in Physics. The Macmillan Co.)

80. Cohesion and adhesion. When a drop of water falls through the air, it draws itself into an almost perfect sphere (Fig. 99). Similarly, lead shot are made by letting molten lead fall from a sieve at the top of a tower into a pool of water at the bottom. In general, a liquid when left to itself tends to get into the shape which has the smallest possible surface. That is, the surface of a liquid acts like a stretched elastic membrane, which contracts whenever it can. This tendency is called **surface tension.**

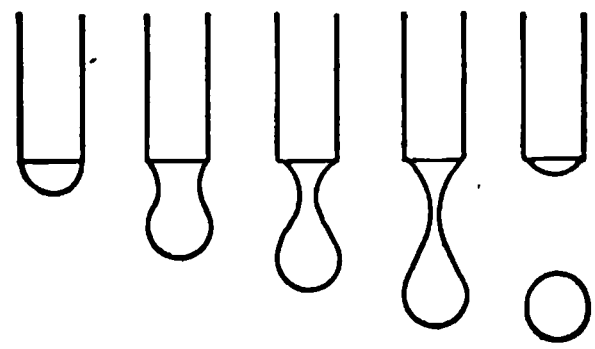

Fig. 99. Pictures showing the formation of a drop.

Surface tension is strikingly shown in soap bubbles. It also explains why a somewhat greasy needle, or even a light flat-bottomed aluminum tea strainer, can be floated on water, although the metal is much

denser than water. Similarly, some kinds of insects can walk on the surface of water, being held up by surface tension.

Surface tension is explained by thinking of a liquid as composed of tiny particles (molecules) which attract each other strongly. It is also observed that there is a great attraction between many pairs of substances if they are brought very close together, as between wood and glue, stone and cement, paint and wood. When this attraction is between particles of the same kind, as in surface tension, it is called **cohesion**, and when between particles of different kinds, it is called **adhesion**.

Fig. 100. Capillary action of water and mercury in small tubes.

81. Capillarity. Suppose we have two U-tubes (Fig. 100) with their side tubes 30 mm. and 1 mm. in diameter. If we pour water colored with ink into the first tube, and mercury into the second tube, we observe that in each case the surfaces in the two sides of the U-tube are not at the same level.

The water wets the surface of the glass and is attracted by it; that is, the adhesion is great. The mercury does not wet the glass, and the cohesion of the particles of mercury for each other makes it appear as if there were repulsion between glass and mercury. The surface of the mercury is convex, and it stands at a lower level in the narrow tube than in the wide one. In the case of water, each tube is drawing the liquid up into itself against the pull of gravity. The narrower the tube, the higher the liquid is raised. Since these small tubes have hairlike dimensions, they are called capillary tubes (from Latin *capillus*, a hair), and this phenomenon is called **capillarity**. It is in this way that liquids rise in wicks, in blotting paper, and in a sponge.

82. Capillarity in soils. After a heavy rain the soil in a garden or a plowed field is full of moisture to a considerable

depth. When the sun shines again, the moisture close to the surface evaporates, but more water is brought up from below through the pores in the soil by capillarity and the evaporation goes on. If, however, the soil near the surface is loosened or pulverized by thorough cultivation, the pores become too big for effective capillary action and surface evaporation is much reduced. Meanwhile capillarity continues to bring water up to where the roots of the plants can use it. Thus the moisture is conserved and put to good use.

Practical Exercise

Water rising in soils. Fill two lamp chimneys with soil. Put at the top of one chimney about 2 inches of fine, dry, loose soil, and in the other chimney pack the soil closely together. Set each chimney in a dish of water. What does this experiment demonstrate? How is this used in dry farming?

SUMMARY OF PRINCIPLES IN CHAPTER III

$$\text{Pressure} = \frac{\text{force}}{\text{area}}. \qquad \text{Force} = \text{pressure} \times \text{area}.$$

For liquids with a free surface (weight of liquid the only thing that counts):

Pressure is
- Independent of direction,
- Proportional to depth,
- Proportional to density of liquid,
- Equal to weight of a column of liquid with a base one unit square and a height equal to the depth.

Average pressure on a surface = pressure at center of surface.

Total force on a surface = area × average pressure.

For liquids under pressure (weight of liquid negligible in comparison):

Pressure is transmitted undiminished in all directions.

Force varies as area.

Archimedes' principle:

The loss of weight of a body either partly or wholly submerged in a liquid is equal to the weight of the displaced liquid.

If the body just floats, this loss of weight is also equal to the weight of the body.

$$\text{Density} = \frac{\text{weight of body}}{\text{volume of body}}.$$

$$\text{Specific gravity} = \frac{\text{weight of body}}{\text{weight of equal volume of water}}.$$

In the metric system, since 1 cu. cm. of water weighs 1 gram, density (g. per cm.^{3}) = (numerically) specific gravity.

In the English system, since 1 cu. ft. of water weighs 62.4 lbs., density (lb. per ft.^{3}) = (numerically) 62.4 $\times$ specific gravity.

To get specific gravity:

Find weight of body.

Find weight of equal volume of water.

Divide weight of body by weight of equal volume of water.

To get weight of equal volume of water:

1. **Compute volume. Weight of water = volume $\times$ density of water.**
2. **Loss of weight of body when wholly submerged = weight of equal volume of water. (May have to use sinker.)**
3. **Weigh equal volumes of liquid and of water in a bottle.**
4. **Find loss of weight of a solid in the liquid and in water. (May use either sinker or float, *i.e.*, hydrometer.)**
5. **Use balancing columns (see laboratory manual).**

To get horse power of water wheels:

$$\text{H.P.} = \frac{\text{weight of water per min. (lbs.)} \times \text{head (ft.)}}{33{,}000} \times \text{efficiency}.$$

The surface of a liquid tends to contract and become as small as possible (surface tension).

Liquids are raised in tubes which they wet and are depressed in those which they do not wet (capillarity).

QUESTIONS

1. What advantages has the hydraulic press for testing steam boilers?

2. What device is used to prevent the oil or water from leaking out around the pistons of a hydraulic press?

3. How is Archimedes supposed to have done his famous experiment with the crown?

4. When a ship passes from a river, where the water is fresh, into the ocean, does it rise or sink in the water?

5. How could you determine the specific gravity of a solid soluble in water, but insoluble in kerosene?

6. What is the water pressure in your laboratory?

7. Two faucets in a town show the same pressure on the gauge and are the same size. If one is one mile from the reservoir, and the other is two miles away, will each faucet deliver the same quantity of water per minute when opened wide?

8. Sometimes when a faucet is opened, especially on an upper floor, the water comes with a rush at first and much more slowly after it has been running a few seconds. Explain.

9. Why does one need to take temperature into account in using the lactometer?

10. What metals float in mercury?

11. How can one pour a liquid out of a glass with the aid of a spoon or glass rod, so that it will not run down the side of the glass?

12. Explain the action of a towel.

13. Explain the process of " fire-polishing " the broken end of a glass tube.

14. If you know the displacement of a battleship, how can you find its weight?

15. Why does one use snowshoes in walking over deep snow?

16. Why is it easier for a swimmer to float in the ocean than in a river?

17. Why should life preservers be filled with cork instead of hay?

18. A schoolboy in Holland is said to have saved his country from a flood by thrusting his arm into a hole in a dike 150 centimeters below the surface of the sea. Could a small boy hold back the whole North Sea?

CHAPTER IV

MECHANICS OF GASES

Weight of the air — vacuum pumps — uses — atmospheric pressure — measured by Torricelli's experiment — barometer — kinds and uses — pumps for liquids — siphon — buoyancy of air — balloons and airships — air compressors — uses — compressibility of gases — Boyle's law — pressure gauges — absorption and diffusion — molecular theory.

83. Pneumatic machines. Just as hydraulic machines make use of the properties of liquids, so **pneumatic** machines make use of the properties of **gases.** Nowadays we often clean our houses with vacuum pumps; we use pneumatic tires on our bicycles and automobiles; we stop our express trains with air brakes; we drive the drills and hammers in our shops with compressed air; and balloons and airplanes are rapidly assuming commercial importance. To understand the operations of all these machines, we must study the properties of gases.

The Atmosphere

84. Density of air. We are so accustomed to having air about us that we do not ordinarily think of it as having either *volume* or *weight.* We speak of an "empty" bottle when we really mean a bottle filled with air. But when we try to fill a narrow-necked bottle with a liquid, we find that we can make the liquid run in only as fast as the air gets out. If we push a glass tumbler mouth down into a pail of water, the glass is not filled with water, because it is filled with air. Air occupies space just as does any other fluid.

Furthermore, air and other gases have *weight,* although we seldom realize this fact.

In order to make it evident that air has weight, let us try the following experiments. Suppose we carefully counterbalance on the scales (Fig. 101) a hollow metal vessel closed with an air-tight valve (a tin can with a bicycle valve soldered into the top will serve). If we then pump more air into the vessel and put it on the scales again, we find that it has gained in weight. If we repeat the process, we find that it weighs a little more after each pumping.

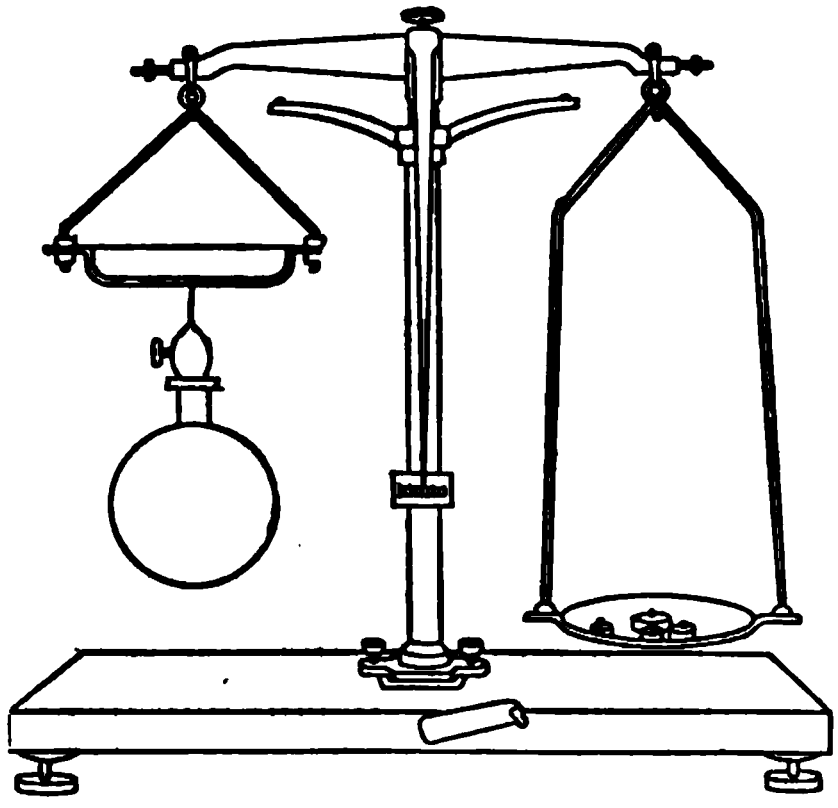

Fig. 101. Proof that air has weight.

In the same way, if we take a vessel from which the air has already been exhausted, such as an electric-light bulb, carefully counterbalance it, and then let the air in by filing off the tip, we find that the scalepan containing the bulb and the broken pieces goes down, showing that the air which has entered has weight.

Careful experiments show that under ordinary atmospheric conditions a liter of air weighs about 1.2 grams, or 1 cubic foot weighs about 1.2 ounces.

Since gases have both **volume** and **weight**, we may express their **densities** in the usual way, as so many grams per cubic centimeter or so many pounds per cubic foot. For example, the density of ordinary air is about 0.0012 grams per cubic centimeter, or 0.076 pounds per cubic foot. Many gases have densities even smaller than that of air. Thus the density of hydrogen under ordinary atmospheric conditions is only about 0.000084 grams per cubic centimeter.

Practical Exercise

Lung capacity. Arrange an apparatus for measuring your own lung capacity and that of your fellow students. What is the normal lung capacity of a person of your age? Which have larger lung capacities,

athletes or non-athletes? Boys or girls? Can you increase your lung capacity by practicing deep breathing for several days or weeks?

85. Vacuum pumps. As long ago as 1650 it occurred to a German, Otto von Guericke, then mayor of Magdeburg, that if air was a substance, he could pump it out of a closed vessel so as to leave the vessel really empty, and that curious effects might be observed in a space that contained nothing at all. Such a space is called a **perfect vacuum**, and a space from which part of the air has been removed is called a **partial vacuum.** Vacuum pumps were formerly found only in physical laboratories, but now they are used so extensively in vacuum cleaners, in making incandescent lamps and X-ray bulbs, and in maintaining a vacuum in the condensers of steam engines, that they are of great commercial importance.

A simple form of mechanical vacuum pump is shown in figure 102. It consists of a metal cylinder *C* fitted with a piston, and having at the lower end two short tubes *A* and *B*, within which are self-acting conical valves, so arranged that the air enters at *A* and leaves through *B*. When the piston is raised, the air in the vessel *R*, which is to be exhausted, expands into the cylinder *C* through the valve *A*. When the piston is pushed down, it compresses this air, closing the valve *A* and opening the outlet valve *B*. Thus with each double stroke a certain fraction of the air in the vessel *R* is removed, this fraction being the ratio of the volume of *C* to the combined volume of *C* and *R*.

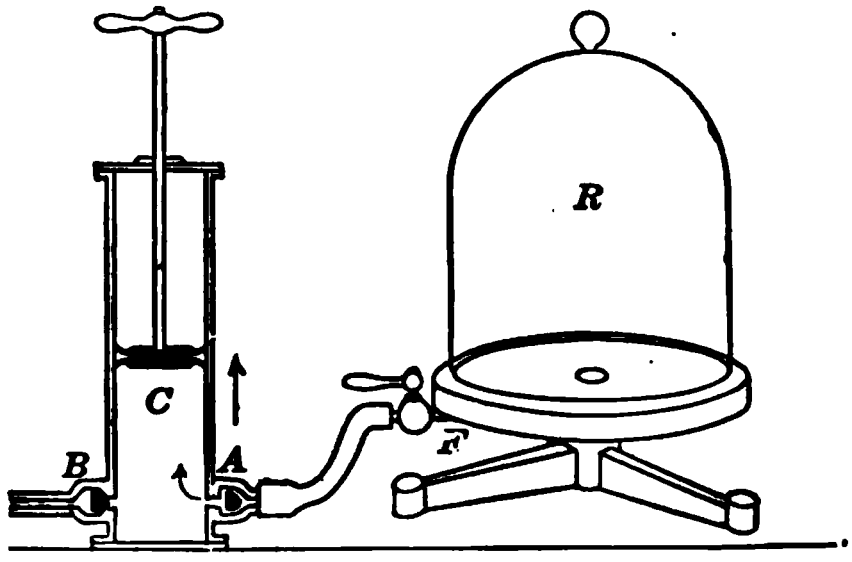

Fig. 102. A simple vacuum pump and receiver.

It will be seen that even with a mechanically perfect pump we never take out quite all the air; for by each stroke we remove only a *certain fraction* of the air, and the remainder expands to fill the vessel. In practice, no pump is perfect, because of leakage. To reduce this, it is common, in high-vacuum pumps, to cover the piston and the valves with oil, and in some forms made of glass the piston is replaced by a column of mercury.

86. Applications of the vacuum pump. **Vacuum cleaning** is an application of the "force of suction," created by a vacuum, to the cleaning of buildings and their furnishings. In the portable vacuum cleaner (Fig. 103), an electric motor is used to drive a fan which sucks in the dirt through a nozzle resting on the surface to be cleaned. The particles of dirt pass with the air stream through the fan into a bag attached to the machine and are there strained out, the air escaping through the sides of the bag. In many modern buildings there is one large vacuum cleaner in the basement to which suction pipes run from the various rooms. A rubber hose carrying a cleaning tool, or nozzle, can be attached to any one of the suction pipes. In this type the dirt is usually strained out of the air before the latter reaches the vacuum pump.

Fig. 103. Portable vacuum cleaner.

In pumping the air from **incandescent-lamp bulbs**, only a small space needs to be exhausted, but the desired vacuum is very high. Usually less than one-millionth part of the air is left in the bulb. For this work two mechanical pumps are used in tandem, one to take the air directly from the bulb, and the other to take it from the cylinder of the first pump. The remaining air is still further removed by burning phosphorus or some other combustible in the bulb. **X-ray tubes** are made in much the same way, except that the process must be continued longer so as to produce a still higher vacuum.

The **pneumatic dispatch tubes** used in department stores for carrying cash and in some cities for carrying mail have a vacuum pump at one end. The articles to be sent are placed in leather cases which fit snugly in the metal tube and are sucked through it.

Large vacuum pumps are also used to pump out of steam condensers such air as leaks into them through the imperfect joints in the steam piping, and also such air as enters the system dissolved in the water fed to the boilers (see section 104). Without such pumps this air would gradually accumulate in the condenser and destroy the vacuum there.

Vacuum pumps are also used in chemical laboratories, and in factories where fruit juices, condensed milk, or other food products are made, to cause rapid evaporation at low temperatures (see section 205).

Problems

1. If a liter of air weighs 1.2 grams, what is the total weight of the air in a room 3 meters high, 10 meters long, and 8 meters wide?

2. Measure the dimensions of some large rectangular room in feet, and then calculate the number of pounds of air which it contains. (Assume that 1 cubic foot of air weighs 0.076 pounds.)

3. What would be the total weight in tons of the gas in the British dirigible balloon R–34 (capacity 2,000,000 cubic feet) if the gas were pure hydrogen? (Assume density of hydrogen to be 0.0053 pounds per cubic foot.)

4. How much difference does it make in the total weight of the gas in the R–34 if one tenth of the hydrogen is replaced by air through leakage and diffusion? (Assume density of air to be 0.076 pounds per cubic foot.)

5. A vacuum pump whose cylinder is 500 cubic centimeters is used to exhaust the air from a liter flask. What is the density of the air left in the flask after 3 complete strokes? (Hint. — Find what fraction of the air is left after each stroke.)

Practical Exercise

Suction of a vacuum cleaner. Test with an open manometer the fan suction of a vacuum cleaner. (For details see *Good's* Laboratory Projects in Physics. The Macmillan Co.)

87. Pressure of the atmosphere. Since we are living at the bottom of an ocean of air, and this air is a fluid which has weight, it is natural to expect that it exerts a pressure. Ordinarily we are not aware of this pressure, because it pushes up on the bottoms of objects almost as much as it pushes down on the tops of them. By getting rid of this upward pressure underneath, we can see how great the downward pressure on top really is. This can be done with a vacuum pump, or in part even with the lungs.

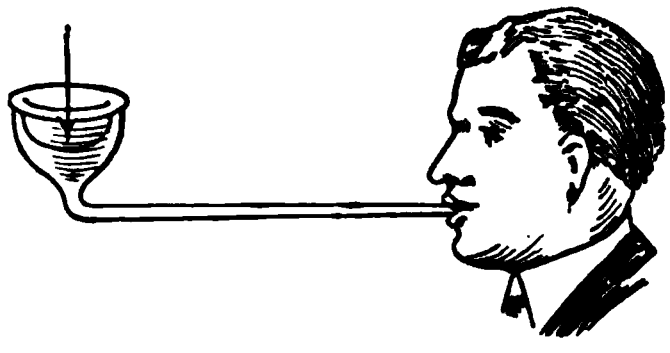

Fig. 104. Removing the upward pressure of the air.

Let us fasten a piece of sheet rubber over the end of a thistle tube, as shown in figure 104. If we suck the air out of the bulb with the mouth, the rubber is forced downward by the atmospheric pressure.

This experiment is even more striking when performed with a larger membrane and with a vacuum pump. If we tie a piece of rubber over the mouth of the glass vessel shown in figure 105, and gradually pump out the air, the rubber will be pushed down more and more by the pressure of the air above it, until it finally bursts. If a piece of bladder is used instead of rubber, it will break with a loud report.

One of the most interesting of Otto von Guericke's experiments was that with his famous "Magdeburg hemispheres." These were two hollow hemispheres about 22 inches in diameter which fitted together so well that the air could be pumped out from between them. The pressure of the surrounding atmosphere then held them together firmly. In a test before the Reichstag and the Emperor, it required sixteen horses, four pairs on each hemisphere, to pull them apart (Fig. 106).

Fig. 105. Pressure of the air breaking a membrane.

88. "Nature abhors a vacuum." The ancients tried to explain many phenomena by saying that "nature abhors a vacuum"; but when the great Italian philosopher, Galileo (Fig. 107), found that a suction pump would not raise water more than 33 feet, he remarked that nature's horror of a vacuum was a curious emotion if it stopped suddenly at 33 feet. He already knew both that air has weight and that the "resistance to a vacuum" was measured by a column of water about 33 feet high. Yet he left it to his friend and successor, Torricelli, to unite these two ideas.

89. Torricelli's experiment. In 1643, Torricelli devised a means of measuring this "resistance" which nature "offers to a vacuum" by a column of mercury in a glass tube instead of a column of water.

Fig. 106. The experiment with the Magdeburg hemispheres, performed by Otto von Guericke in 1650 before the German emperor.

We may repeat this experiment if we take a stout glass tube about 3 feet long, closed at one end, and fill it completely with mercury. If we close the opening with the finger, invert the tube, and put its open end into a dish of mercury, we observe that, when the finger is removed, the mercury in the tube (Fig. 108) sinks to a level about 30 inches above the mercury surface in the dish (if this experiment is done at sea level). If we incline the tube to one side, the metal fills the entire tube and hits the top of the glass with a sharp click. The space above the mercury is empty except for a minute quantity of mercury vapor. It is, indeed, the most perfect vacuum that we know how to make.

Fig. 107. Galileo Galilei (1564–1642). Often called "the father of modern science" because he was one of the first to test his theories with experiments.

Fig. 108. Torricelli's experiment—balancing the pressure of the air with a mercury column.

The column of mercury in the tube just balances the pressure of the atmosphere on the mercury in the larger vessel. In other words, liquids rise in exhausted tubes because the pressure exerted by the atmosphere on the surface of the liquid outside pushes the liquid up the tube, and not because of any mysterious sucking power created by the vacuum.

90. How to calculate the pressure of the atmosphere from Torricelli's experiment. From the law that pressure in a liquid is everywhere the same at the same depth, we know that when the mercury is held up in the inverted tube, the pressure in the

tube at *a* (Fig. 109) is the same as at the surface outside, where it is exerted by the atmosphere. At *a* it is exerted by the column of mercury *ab*. Under standard conditions, the height *ab* is about 76 centimeters, and the pressure at *a* is therefore equal to the weight of a column of mercury 76 centimeters high and 1 square centimeter in cross section. This is the weight of 76 cubic centimeters of mercury, or 76 times 13.6 grams, or 1034 grams.

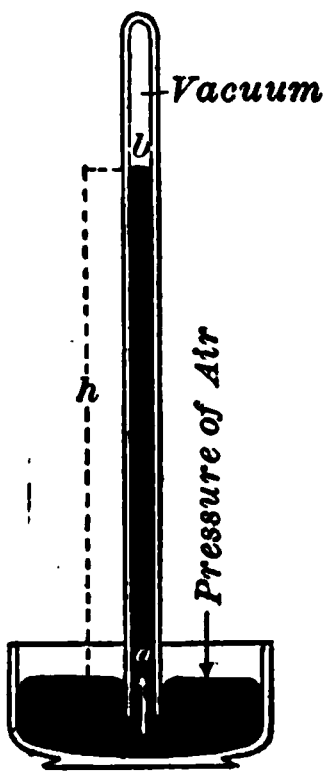

Fig. 109. Measuring the pressure of the air with a mercury column.

In the English system the pressure of the atmosphere is equal to the weight of a column of mercury about 30 inches high and 1 square inch in cross section; that is, 30×0.49, or 14.7 pounds. Roughly, then, *one "atmosphere" is about 1 kilogram per square centimeter, or about 15 pounds per square inch.*

91. Pascal's experiments. In 1648, Pascal reasoned that if the mercury column were held up simply by the pressure of the air, the column ought to be shorter at a high altitude. So he carried a Torricelli tube to the top of a high tower in Paris, and found a slight fall in the height of the mercury column. Desiring more decisive results, he wrote to his brother-in-law to try the experiment on a mountain in southern France. In an ascent of 1000 meters, the mercury sank about 8 centimeters, which greatly delighted and astonished them both.

Pascal also tried Torricelli's experiment, using red wine and a glass tube 46 feet long, and found that with a lighter liquid a higher column was sustained by the air pressure.

92. The barometer. The arrangement constructed by Torricelli may be set up permanently as a means of measuring the pressure of the atmosphere. It is then called a **barometer.** To "read the barometer" means simply to measure accurately the height of the mercury column above the surface of the liquid in the reservoir. In the form of barometer

shown in figure 110, this reservoir has a flexible bottom which may be raised so as to bring the surface of the pool of mercury just up to the tip of an ivory point projecting into the reservoir. The height of the mercury in the tube is then read off on a scale attached to the tube.

A more convenient form to carry about is the aneroid, or metallic barometer (Fig. 111). As the name indicates, it is "without liquid," and consists essentially of a disk-shaped metal box, which has a thin corrugated top. When the air has been pumped out of the box, it is sealed up, its top being supported by a stout spring to prevent its collapsing. As the pressure of the air changes, the top of the box moves up or down, and the small motion is greatly magnified by means of levers and a delicate chain, and is communicated to a pointer which moves over a scale. A hairspring serves to take up the slack of the chain. The scale is graduated to correspond to the readings of a standard mercurial barometer. Aneroid barometers are made in various sizes. Some are even as small as ordinary watches.

Fig. 110. Mercury barometer. (Fortin type.)

93. Uses of the barometer. The barometer indicates changes in atmospheric pressure. These changes may be due to fluctuations in the atmosphere itself or to changes in the elevation of the observer.

If a barometer, kept always at the same elevation, is frequently observed, or if it makes a continuous record, as does a barograph (Fig. 112), it is found to fluctuate according to the weather. Experience shows that a "falling barometer," that is, a sudden decrease of atmospheric pressure, precedes a storm; and a "rising barometer," that is, an increasing atmospheric pressure, indicates the approach of fair weather; while a steady "high barometer" means settled fair weather.

The Weather Bureau takes barometric readings simultaneously at many different places, and the results are telegraphed to central stations, where weather maps are prepared. On these maps it is observed that there are certain broad areas where the pressure is low,

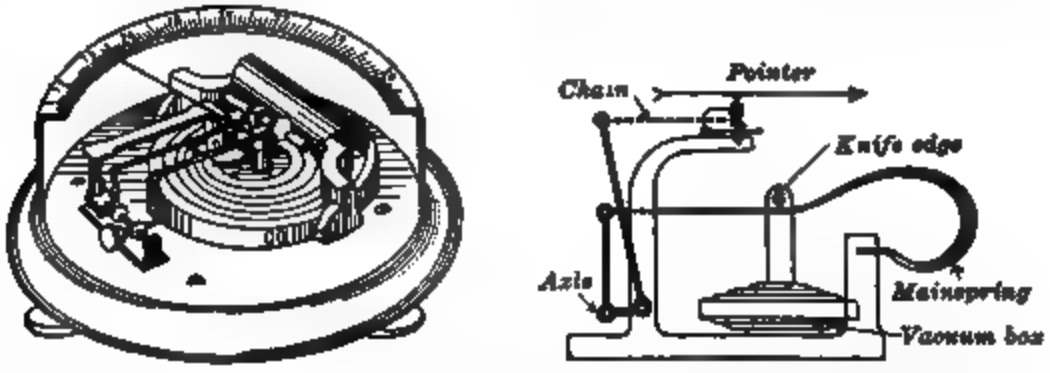

Fig. 111. Aneroid barometer with diagram to show its principle.

and other regions where the pressure is high. The areas of low barometric pressure are usually storm centers, which generally move in an easterly direction. If we know where these low-pressure areas are located and their probable movement, we may predict the weather.

Fig. 112. Barograph, or self-recording barometer.

Figure 113 shows a portion of a government weather map. The curved lines, showing the places where the barometric pressure is equal, are called isobars. The direction of the wind at various places is indicated by an arrow. A careful study of these phenomena (which is called meteorology) shows that " lows " are really great eddies of air slowly moving in a counter-clockwise direction.

Another important use of the barometer is to measure the **difference in altitude between two** places. If a surveyor or explorer carries a barometer up a mountain, he notices that it indicates a decrease in atmospheric pressure as he ascends. For places not far above sea level this decrease is about 1 millimeter for every 11 meters of elevation, or 0.1 of an inch for every 90 feet of ascent. Aneroid barometers graduated in feet or meters are carried by balloonists and aviators to tell how high they are. The curve in figure 114 shows the average atmospheric pressure at various altitudes. The maximum altitude shown for an airplane has probably already been exceeded. It will be seen that the rate of decrease in pressure is not uniform but becomes less at high altitudes. Why?

Fig. 113. Portion of a weather map.

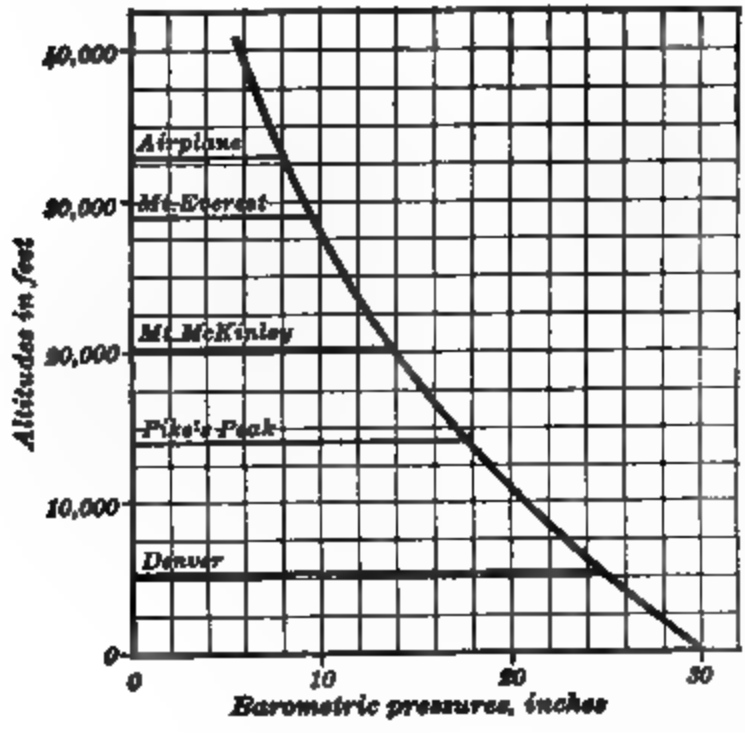

Fig. 114. Curve showing the relation between atmospheric pressure and altitude.

QUESTIONS AND PROBLEMS

1. Why is it not necessary to hang a barometer out of doors to measure atmospheric pressure?

2. Why is it necessary to hang a mercurial barometer in a vertical position?

3. In repeating Torricelli's experiment, why is it necessary to have the bore of the tube and the mercury very clean?

4. Why does a rubber tube often collapse when the air inside is exhausted?

5. Otto von Guericke is said to have built a water barometer which projected above the roof of his house. A wooden image floated on the surface of the water in the tube. Why are water barometers not generally used?

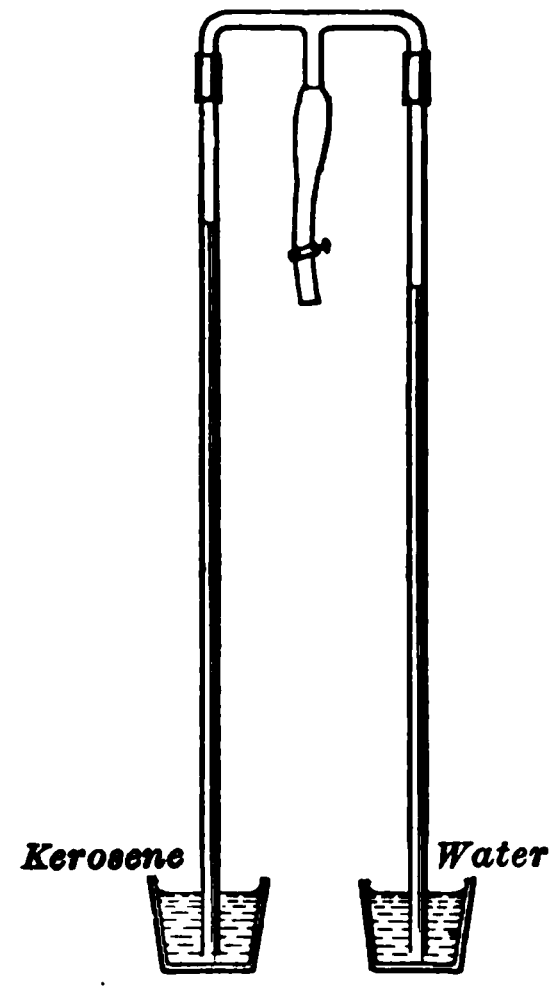

Fig. 115. Specific gravity by balanced columns.

6. A diver works 51 feet below the surface of fresh water. To how many atmospheres of pressure is he subjected?

7. When the barometer reads 74.5 centimeters, how many inches does it read?

8. When a mercury barometer reads 76 centimeters, what does a glycerin barometer read? (The density of glycerin is 1.26 grams per cubic centimeter.)

9. When the barometer reads 75 centimeters, what is the atmospheric pressure in grams per square centimeter?

10. During a storm the barometer "dropped" 1.5 inches. How far would a water barometer have fallen?

11. If a certain pressure is 75 pounds per square inch, how many kilograms per square centimeter is it?

12. During a mountain climb the barometer falls 1.75 inches. What is the net height climbed (in feet)?

13. Two glass tubes are arranged vertically (Fig. 115) so that their lower ends dip into water and kerosene, respectively, while their upper ends are joined to a mouthpiece. When some of the air in the tubes is sucked out, the water rises 26 centimeters and the kerosene 33 centimeters. Find the specific gravity of the kerosene. (This is a common way of getting specific gravity.)

14. The original Magdeburg hemispheres are preserved in a museum in Munich. They are about 22 inches in diameter inside. When the air was exhausted, it is said to have required 8 horses on each half to separate them. Assuming that the pressure of the atmosphere was 15 pounds per square inch, find the force exerted by each set of horses. (Hint. — Reckon force on circle 22 inches in diameter. Why?)

15. In the apparatus of figure 115, if, after the columns are sucked up and the pinch-cock on the rubber mouthpiece is screwed up tight, a tiny hole were bored through the wall of the glass tube halfway up the water column, would the water in the upper part of the tube run out through the hole?

Practical Exercise

Making a barometer. Construct a J-tube mercurial barometer. Use strong glass tubing (about 1 cm. diameter). It is easier to fill the tube if the bend is made of thick-walled rubber tubing. Mount it on a board and use a sliding meter stick to measure the height of the mercury column.

94. Pumps for liquids. The ancients used pumps to lift water from wells, even though they did not know why a pump works; they thought it was because "nature abhors a vacuum." We know now that the underlying principle is the same as in a mercurial barometer: it is the pressure of the atmosphere on the surface of the water in the well that pushes the water up into the pump.

The ordinary **suction pump** (Fig. 116) consists of a cylinder C, which is connected with the well or cistern by a pipe T. At the bottom of the cylinder is a clapper valve S, opening up. A piston P can be worked up and down in the cylinder by means of a handle. This piston also contains a valve V opening up. On the *upstroke* of the piston P, the valve V remains closed because of its weight and the pressure of the water and air above it. Between the piston and the bottom of the cylinder there would be a partial vacuum if the valve S remained closed. But the pressure of the air on the water in the well forces some water up through the pipe T, past the valve S into

Fig. 116. A suction or lift pump.

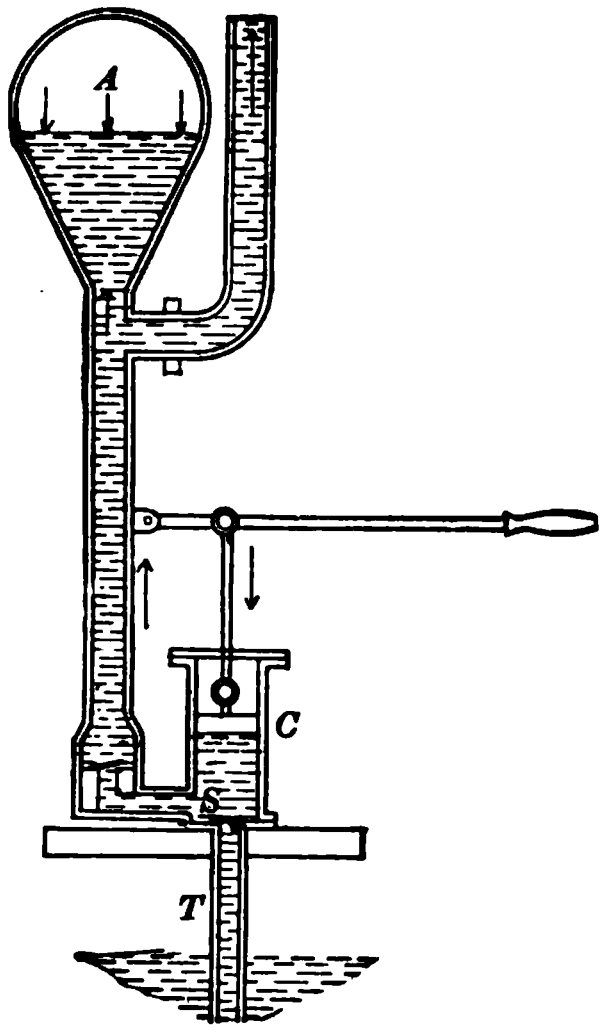

Fig. 117. A force pump with an air dome.

the cylinder *C*. On the *down stroke* of the piston the valve *S* closes, the valve *V* opens, and the water gets above the piston. On the next up stroke it is lifted out through the spout. The valve *S* must never be more than 34 feet above the water in the well, and in practice this distance is seldom more than 30 feet. Why?

Another kind of pump, shown in figure 117, is called a **force pump.** The suction pipe *T* with its valve *S* are exactly like the corresponding parts of the house pump just described, but the piston has no opening through it, and the outlet pipe and a second valve are at the bottom of the cylinder. Raising the piston fills the cylinder with water; pushing it down again forces the water out through the second pipe. If enough force is exerted on the piston, the water can be pushed up to a considerable height. The pump can therefore be located near the bottom of a well or mine shaft.

Since the water is forced up only on the down stroke, it comes in spurts. To reduce the jar and shock, an air chamber *A* is connected with the delivery pipe, so that the air may act as a cushion or spring. Power pumps, such as are used on fire engines or in city waterworks, are " double-acting " (Fig. 118), and give a still steadier stream.

When a large volume of water is to be lifted a short distance, a **centrifugal pump** (Fig. 119) is used. This is something like a water wheel worked backwards. As the wheel inside (Fig. 120) is turned, the water, which enters near the hub, gets caught between the blades and is hurled outward into the delivery space around the wheel, even against some pressure there. Cen-

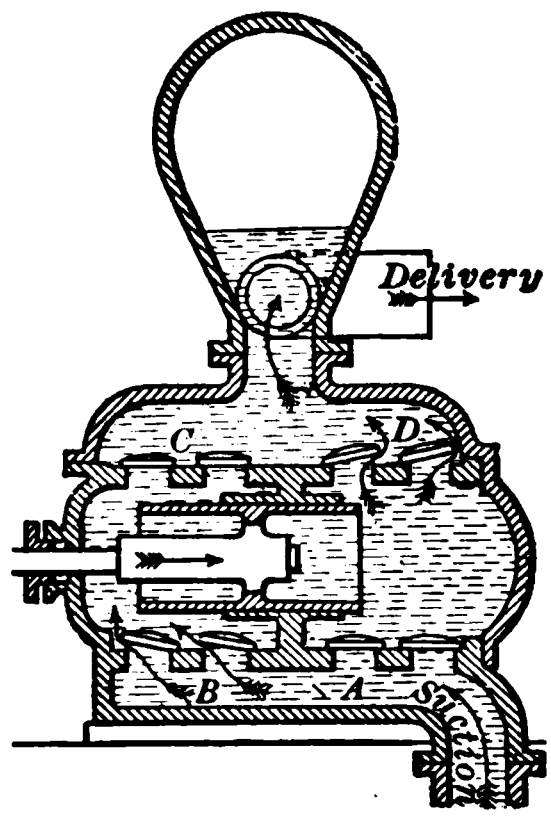

Fig. 118. A double-acting force pump with air cushion on top.

trifugal pumps are often used to circulate the water in the cooling system of automobiles and also to circulate the oil. Similar machines, called blowers, are used to force a current of air through a building for ventilation, to make "forced draft" for furnaces, and to create

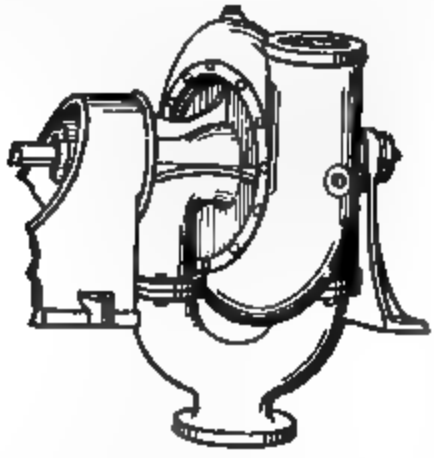

Fig. 119. Centrifugal pump. The water is drawn in near the center on both sides.

Fig. 120. Vertical section of a centrifugal pump.

the suction in portable vacuum cleaners. Often several of these blowers are used in series to give higher pressures. Large blowers, driven by steam turbines, are used with blast furnaces, because of the extremely steady rate at which they furnish the air needed for combustion.

95. Siphon. The siphon is a bent tube with unequal arms. It is used to empty bottles and tanks which cannot be easily tipped, or to draw off the liquid from a vessel without disturbing the sediment at the bottom. If the tube is filled and placed in the position shown in figure 121, the liquid will flow out of the vessel A and be discharged at a lower level D. The force which makes it flow is the weight of the column of water CD, which is between the water level AA' and the water level DD'. If the water level DD' is raised to AA', this moving force becomes nothing and the water ceases to flow; if the level DD' is lifted above AA', the liquid flows back into the vessel A. A siphon works, then, as long as the free surface of the liquid in one vessel

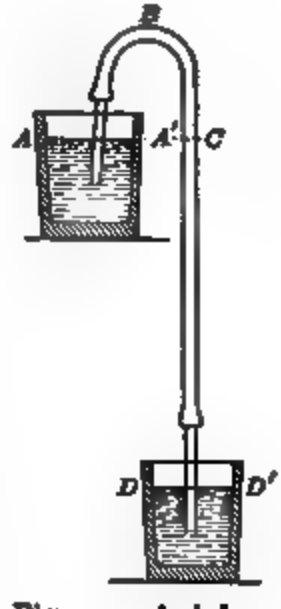

Fig. 121. A siphon.

is lower than the free surface of the liquid in the other vessel. A water siphon will not work if the top of the bend B is more than 34 feet above the level AA'. Why?

Siphons are often used on a large scale in engineering. For instance, in power plants the water used to condense the steam is often taken from the ocean, raised 10 or 15 feet to the condenser, and carried back to the ocean, through a pipe that is everywhere air-tight and acts like a siphon. The only work that the pumps have to do is to keep the water moving against the friction in the pipe. Siphons are also used in aqueducts to carry water over hills. In such cases air bubbles carried along in the water tend to collect at the top of each hill, and so small air pumps have to be installed to keep the pipes full of water.

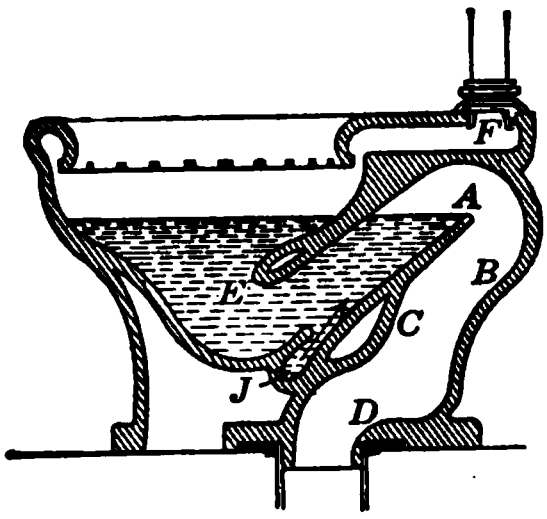

Fig. 122. Cross section of a jet-siphon water-closet.

Siphon action also plays a part in modern water-closets (Fig. 122). The siphon EAD is not completely filled with water, but the shape of the long arm AD is such that the sheet of water that flows over the lip at A strikes successively at B, C, and D, making gas-tight seals across the pipe. Meanwhile, the flowing water carries air along with it, producing a partial vacuum near A. This sucks over the water in the bowl until the level drops far enough to let air flow past the seal at E. In **jet-siphon closets** an auxiliary jet J (Fig. 122) is fed from the water supply F by a diagonal passage along the side of the bowl. This jet points up the short leg EA and helps to get the flow started quickly and quietly.

Practical Exercise

Rate of flow of a siphon. Measure the time required to empty a given pail of water with a siphon. Repeat, using a longer tube and greater difference in level. Study the effect of increasing the height from the water in the pail to the bend in the siphon.

96. The buoyancy of air. We have seen that as one climbs a mountain, the pressure of the air decreases. A sensitive barometer will indicate a decrease of pressure even when it is lifted from the floor to a table. Therefore the upward pressure of the air on the bottom of any object is slightly

more than the downward pressure of the air on its top. In other words, just as in the case of liquids, *there is a lifting effect on everything surrounded by air.* This lifting effect is *equal to the weight of the air which is displaced* (Principle of Archimedes).

To make this principle of the buoyancy of the air seem more real, let us balance a hollow brass globe against a solid piece of brass under the receiver of a vacuum pump (Fig. 123). When the air is pumped out, the globe seems to be heavier than the solid brass weight, because the support of the air around it has been withdrawn. If the air is readmitted rapidly, the rise of the globe will be very apparent.

Fig. 123. Lifting effect of air.

Most things are so heavy in comparison with the amount of air they displace that this loss in weight, due to the buoyancy of the air, is not taken into account. For example, a barrel of flour would weigh about 8 ounces more *in vacuo* than in air. But if the volume of air displaced is very large in comparison with the weight, as in the case of a balloon, the object is lifted just as a piece of wood is lifted when immersed in water.

97. Balloons and airships. The envelope, or bag, of a **balloon** (Fig. 124) is made of two or three layers of thin rubberized cotton or silk cloth, or sometimes of goldbeater's skin strengthened with cloth, so as to be light, strong, and as nearly gas-tight as possible.

Fig. 124. U. S. Army spherical balloon.

Free balloons are spherical because this gives the greatest volume for a given amount of fabric. A wicker basket to carry passengers, instruments, and ballast is suspended from a rigging, which, in the case of a free balloon, is a great net of light cords that envelops the balloon. The bag is usually filled with hydrogen, although illuminating gas or even heated air may be used for short trips.

An **airship** is a dirigible balloon provided with propellers and gasoline engines and with horizontal and vertical rudders. An airship is shaped more or less like a sausage and has a pointed nose and tail so as to reduce the head resistance as it moves through the air. An airship of the Zeppelin type, such as the R-34 which flew across the Atlantic in 1919,

Fig. 125. Dirigible airship of the rigid type.

has a huge **rigid framework** (Fig. 125), made of a very light and strong alloy of aluminum, and covered with light, weatherproof fabric. Inside are 15 to 20 separate hydrogen bags, each in a compartment of the frame. The crew of such an airship can climb all over its interior between the hydrogen bag and the outer envelope to make repairs. In the smaller types there is only one gas bag, which is held in shape by the excess pressure of the gas inside. In **nonrigid** ships (Fig. 126), one or more cars are suspended by cables attached to reënforcing patches sewed to the fabric of the bag. In **semirigid** ships, there is a stiff keel the whole length of the bag, which gives it some stiffness and carries the cars.

One great danger in ballooning is from fire. In war time

Fig. 126. U. S. non-rigid dirigible C-7, photographed in Washington, D. C., December, 1921, on the occasion of the first public balloon flight ever made with *helium*. It contained about 180,000 cubic feet of this rare gas, more than 1000 times as much as the total that had been obtained between 1847, when it was discovered, and 1917, when the United States entered the World War.

incendiary bullets are used, and in times of peace the balloon fabric sometimes gets electrified by friction and a spark discharge may ignite the hydrogen. Also the hot exhaust from the engine is a constant source of danger. Recently **helium** (see figure 126), a non-inflammable gas, has been separated from certain special kinds of natural gas in such quantities that it will probably be used in the airships of the future as a measure of safety against fire.

To compute the total lift of a balloon, we have only to get *the difference between the weight of the air displaced and the weight of the gas in the balloon.* A large part of the total lift is used in raising the weight of the bag, rigging, and car and, in a dirigible, of the engines. The rest, the **disposable lift,** is available for lifting ballast, fuel, passengers, and freight.

QUESTIONS AND PROBLEMS

1. How many feet could water be lifted with a perfect suction pump (*a*) at sea level, and (*b*) in Denver, Colorado (altitude about 5400 ft.)?

2. How many feet could crude oil (density 0.89 grams per cubic centimeter) be lifted out of an oil well by a perfect suction pump at sea level?

3. How much work is needed to lift 100 gallons of water 25 feet with a perfect pump?

4. How much power is needed to raise 100 gallons of water per minute 25 feet with a perfect pump?

5. A force pump is to deliver water at a point 20 feet above the level of its barrel. How great is the water pressure in the barrel when the piston is descending?

6. The piston of a fire-engine force pump is 4 inches in diameter, and the total force exerted on it by the engine is 600 pounds. If the pump acts perfectly, at how great a height will it deliver water?

7. A siphon is to be used to transfer mercury from one bottle to another. How far above the level of the mercury in the higher bottle can the top of the siphon tube be?

8. What is meant by "priming" a dry suction pump? Explain how this process restores the pump to working condition.

9. Explain the operation of the S-trap used under sinks and washbowls (Fig. 127). Why should such traps be ventilated?

10. How would one clean and empty an S-trap?

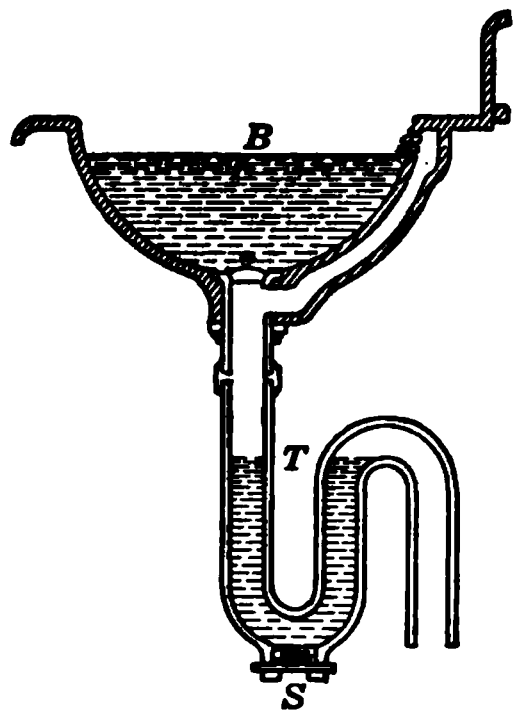

Fig. 127. A washbowl and S-trap.

11. A balloon has a capacity of 37,000 cubic feet and is filled with 95 per cent pure hydrogen (the rest being air). The balloon, rigging, and basket weigh 1000 pounds, and the two passengers each 150 pounds. How much pull is required to hold the balloon down near the ground? (Assume the density of hydrogen is 0.0053 pounds per cubic foot.)

12. An airship has a capacity of 84,000 cubic feet and is filled with 97 per cent hydrogen. The weight of the gas bag and associated parts is 2070 pounds, the weight of the engine, car, tanks, and fuel 1930 pounds, and the weight of the instruments, parachutes, tools, etc. is 350 pounds. If it carries two men weighing together 320 pounds, how many pounds of ballast are needed to give exact equilibrium?

13. The total lift of the R–34 when filled with hydrogen is about 70 tons. Helium is twice as dense as hydrogen. What would be the total lift of the R–34 if filled with helium?

Air under Pressure

98. Pascal's law applies to gases. Gases under pressure act exactly like liquids under pressure in that *each transmits pressure undiminished in all directions, and on all parts of the inclosing wall.*

99. Air compressors. The vacuum pump described in section 85 could also be used as an **air compressor** to pump air from the atmosphere into a closed tank by attaching a tube at *B*. The pressure that could be obtained in the tank would depend on the force applied to the pump handle. Automobile tires require a pressure of from 45 to 75 pounds per square inch; for this purpose a pump driven by an electric motor or a two-cylinder hand pump is generally employed.

The hand pump shown in figure 128 consists of two cylinders C and c and two pistons attached to a common handle. The loosely fitting metal pistons are provided with two cup-shaped leather washers: the one on the large piston P is turned *down*, and the one on the smaller piston p is turned *up*. On the down stroke of the pistons, the air below P is forced over through the connecting passage at the bottom into the small cylinder, and then up past its piston into the hose and tire. On the up stroke, the compressed air above p is forced into the tire; and at the same time air from the outside passes P and fills both cylinders. The valve in the stem of the tire and the valve V in the pump keep the air from flowing back into the small cylinder c. Thus we see that a two-cylinder pump is more effective than a one-cylinder pump, because it forces air into the tire on both the up and the down strokes.

Fig. 128. Two-cylinder automobile-tire pump.

Large air compressors driven by steam engines or electric motors are much used in steel plants, shops, and quarries to furnish a supply of compressed air. This is delivered as a forced draft to blast furnaces, or stored in steel tanks and used to drive all sorts of pneumatic machinery.

100. Uses of compressed air. There are many tools which are driven by compressed air, such as **riveting hammers** for forming the rivet-heads on steel work, and the **pneumatic tools** used in stone cutting, iron chipping, drilling, etc. These are, in general, lighter and simpler than other portable tools, and there is less danger of fire. When such tools are used in mines, the waste air which they discharge helps to furnish ventilation, and this is often an important advantage. **Rock drills, sand blasts** for cleaning metal and stone surfaces, and **air brakes** on electric and steam cars are other common applications. Compressed air is also used to keep the water out of **diving bells** and the open ends of **tunnels** while they are being built under rivers or harbors, and to supply air to **divers.**

101. Air is very compressible. A striking difference between compressed air and water under pressure is that the volume

of the air is much reduced by the pressure while the water is compressed almost not at all. This striking difference can be shown by the following experiment.

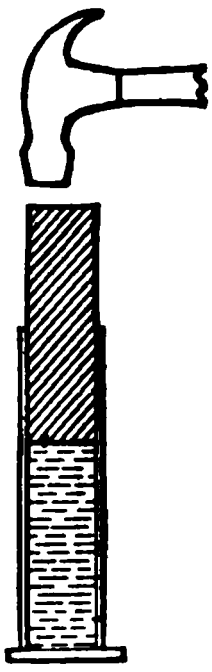

Fig. 129. Compressibility of fluids.

When a brass tube, with a closely fitting steel rod (Fig. 129), is filled with air, the plunger can easily be pushed down by hand. When the plunger is released, it springs back nearly to its initial position. If it does not quite come back to its initial position, it means that some of the air has leaked out. The entrapped air acts like a spring. But when the tube is filled with water, or any other liquid, it is quite impossible to push the plunger down to any perceptible extent by hand; and when the end of the plunger is struck with a hammer, the effect is as if the entire tube were a solid steel column, because the liquid is so nearly incompressible.

This ability of air to yield to a shock and to return promptly to its original condition afterward, that is, its **compressibility** and its **perfect elasticity**, together constitute what is called its **resiliency**. This characteristic is utilized in pneumatic tires and air cushions and in tennis balls and footballs.

102. How volume of air changes with pressure — Boyle's law. The amount of change in the volume of a given quantity of air when the pressure changes was first investigated in 1662 by an Irishman, Robert Boyle, and a few years later by a Frenchman, Mariotte.

These experiments have shown that, *at constant temperature, the volume of a gas varies inversely as the pressure.* This principle is known as **Boyle's law**; it applies to all gases.

This may also be expressed in symbols as follows:

$$\frac{V}{V'} = \frac{P'}{P} \quad \text{(notice the } \textit{inverse} \text{ proportion)},$$

or

$$PV = P'V'$$

where V is a given volume of gas subjected to a certain pressure P, and V' the changed volume when the pressure changes to P' at constant temperature.

We may investigate this question for ourselves by performing the following experiment. Figure 130 shows a large iron cylinder and a small glass tube closed at the upper end and connected with the large cylinder at the bottom. A pressure gauge (Bourdon type) is connected to indicate the pressure directly in pounds per square inch. The whole apparatus is filled about half full of oil, which imprisons a certain amount of air in the top of the glass tube. The pressure is applied by means of a compression pump attached at the top of the iron cylinder. Since the tube is uniform in bore, we may measure the volume of the air within in terms of the length of the air column. If we start with 24 centimeters of air in the tube and with a pressure of 15 pounds per square inch, and pump in air until the pressure is doubled (30 lbs./sq. in.), we find that the volume of the air is reduced to one half the original volume (that is, to 12 cm.). If we pump in more air until the pressure is tripled (45 lbs./sq. in.), we find that the volume of the air is reduced to one third (that is, to 8 cm.).

Fig. 130. Apparatus to demonstrate Boyle's Law.

Evidently, if the pressure on a certain quantity of air is doubled and the volume is halved, the air must become twice as dense. In general, *the **density** of air, or of any gas, varies directly as the pressure at constant temperature.*

The very great decrease in volume that can be produced by a sufficiently high pressure is made use of in storing gases in a very compact form for transportation. Thus, oxygen gas, which is used for welding and cutting, for the treatment of the sick, and for enabling aviators to breathe at very high altitudes, is sold in strong steel cylinders into which it has been compressed to 1800 pounds per square inch.

103. Pressure gauges. Besides barometers, which are really pressure gauges designed for pressures of one atmos-

phere or less, we need gauges for *higher pressures*, such as those in a steam boiler or a compressed-air tank, and gauges for *very low pressures*, such as those in the condenser of a steam engine or the receiver of a vacuum pump.

To measure slight differences in pressure, the **open manometer** is employed, usually with some liquid lighter than mercury as the indicating fluid.

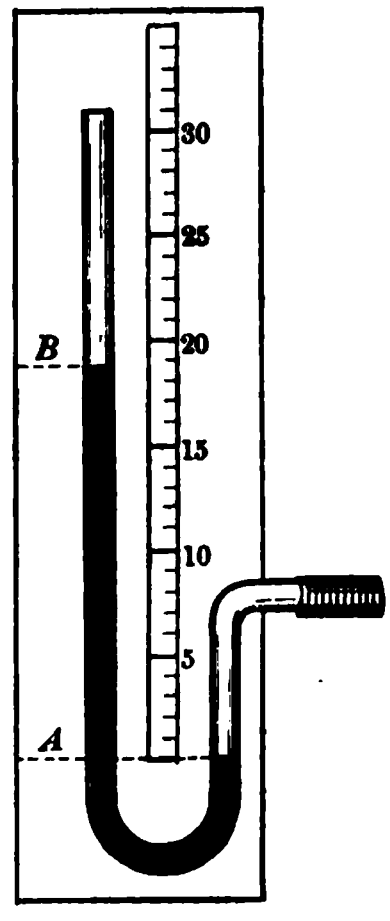

Fig. 131. Open manometer.

If we bend a piece of glass tubing as shown in figure 131, and partly fill the tube with colored water, we have a suitable gauge with which to measure the pressure of ordinary illuminating gas. This will usually cause a difference in the levels *A* and *B* of about 2 inches.

For high pressures this form of gauge, even when filled with mercury, becomes too cumbersome, so a **closed manometer** (Fig. 132) is used. The mercury stands at the same level in both arms when the pressure is one atmosphere. If the pressure is greater than this, the mercury is forced into the closed arm, compressing the confined air according to Boyle's law. The scale may be made to read in atmospheres.

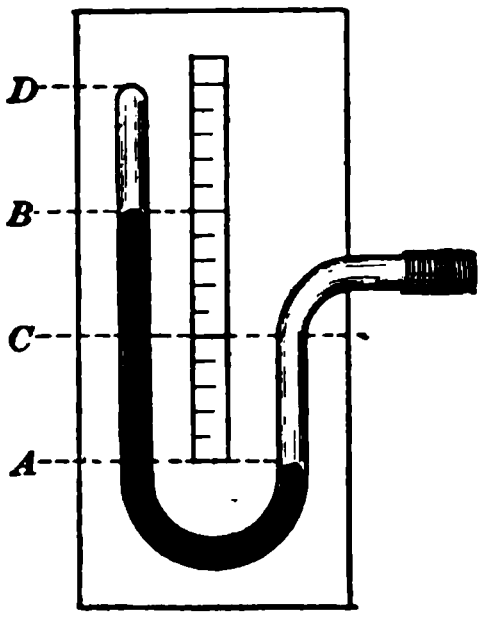

Fig. 132. Closed manometer.

For practical work the **Bourdon spring gauge** (section 76) is used. Such gauges are usually graduated so as to read zero when the pressure is really one atmosphere; that is, they indicate the difference between the given pressure and atmospheric pressure. Therefore, when an engineer speaks of a pressure of 100 pounds **by the gauge**, he means 100 pounds per square inch *above* one atmosphere; when he means the total pressure above a vacuum, he usually says 100 pounds **absolute**.

When pressures less than one atmosphere are to be measured, such as the vacuum in the condenser of a steam engine (section 227), a barometer of the ordinary form would be inconvenient, because the whole reservoir, or cup, at the bottom would have to be exposed to the pressure which is to be measured. The gauge is, therefore, arranged so as to admit the low pressure to be measured to the top of the barometer tube. The height of the mercury then indicates the *difference* between the small pressure and that of the atmosphere. The better the vacuum, the higher such a gauge reads. Thus engineers usually speak of a 26- or a 28-inch vacuum, meaning a pressure less than the standard 30-inch atmosphere, by 26 or 28 inches of mercury. The best vacuums now obtained in steam turbine condensers are from 29 to 29.5 inches. Since these mercury gauges would be inconvenient in engine houses, Bourdon gauges are used. They are graduated to read in inches like the mercury gauges which they replace.

Practical Exercises

1. Blood pressure. Find out how a physician measures a patient's blood pressure. Draw a careful diagram of the apparatus. What is the function of the pressure sleeve? In what unit is blood pressure expressed?

2. Gasoline measuring pump. Figure 132A shows a common type of gasoline measuring pump. Is it a lift or a force pump? Describe carefully its construction and operation.

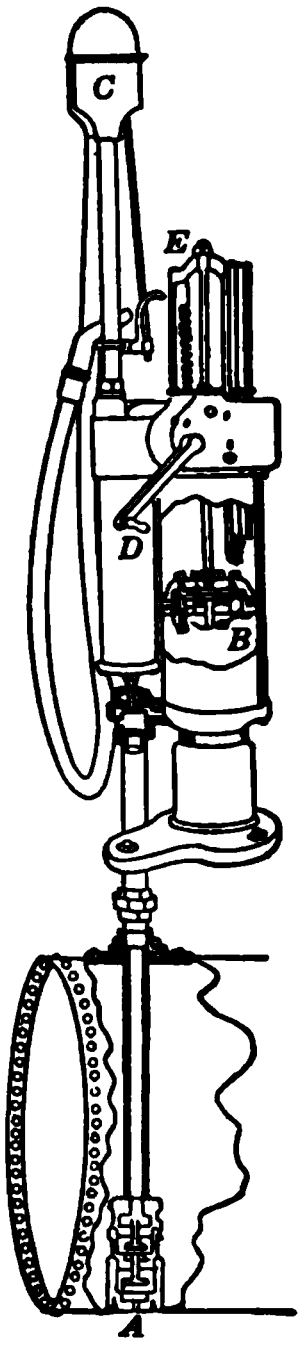

Fig. 132A. Gasoline pump.

Questions and Problems

(Assume constant temperature in these problems.)

1. One hundred cubic feet of air under a pressure of 15 pounds per square inch absolute are compressed to 300 pounds per square inch absolute. What does the volume become?

2. The volume of a tank is 2 cubic feet, and it is filled with compressed air until the pressure is 3000 pounds per square inch absolute. How many cubic feet of air under a normal pressure of 15 pounds per square inch absolute were forced into the tank?

3. An oxygen cylinder charged to 1800 pounds per square inch absolute contains gas enough to occupy 200 cubic feet at atmospheric pressure. What is the internal volume of the cylinder?

4. What is the net force applied to a brake piston 10 inches in diameter, when the pressure by the gauge is 80 pounds per square inch? (Remember that the atmosphere is pressing against the other side of the piston.)

5. One hundred cubic feet of air at a pressure of 15 pounds per square inch are compressed to 36 cubic feet. What is the pressure then?

6. Oxygen is sold in steel cylinders under a pressure of 1800 pounds per square inch absolute. As the gas is used, the pressure drops. When it has dropped to 600 pounds absolute, what fractional part of the original gas remains? Give your reasoning.

Other Less Important Properties of Gases

104. Absorption of gases in liquids. If we slowly heat a beaker containing cold water, small air bubbles are seen to collect in great numbers upon the walls (Fig. 133) and to rise through the liquid to the surface. It might seem at first that these are bubbles of steam, but they must be bubbles of air, first because they are formed at a temperature below the boiling point of water, and second because they do not condense as they come to the cooler layers of water above.

This simple experiment shows that ordinary water contains dissolved air, and that the amount of air which water can hold decreases as the temperature rises. It is the oxygen of the air that is dissolved in water which supports the life of fish. The amount of gas absorbed by a liquid depends on the pressure of the gas above the liquid. Thus, soda water is ordinary water which has been made to absorb large quantities of carbon dioxide gas by pressure. When the pressure is relieved, the gas escapes in bubbles, causing effervescence. Careful experiments show that the amount of gas absorbed is proportional to the pressure. The amount of gas which will be absorbed by water varies greatly with the nature of the gas. For example, at 0°C. and at a gas pressure of 76 centimeters of mercury, 1 cubic centimeter of water will

Fig. 133. Bubbles of air in water.

absorb 0.049 cubic centimeters of oxygen, 1.71 cubic centimeters of carbon dioxide, and 1300 cubic centimeters of ammonia gas. The ordinary commercial aqua ammonia is simply ammonia gas dissolved in water.

105. Absorption of gases in solids. Certain porous solids, such as charcoal, meerschaum, silk, etc., have a great capacity for absorbing gases. For example, charcoal will absorb 90 times its volume of ammonia gas and 35 volumes of carbon dioxide. It is this property of charcoal which makes it useful as a deodorizer. This absorption seems to be due to the condensation of a layer of gas on the surface of the body or of the pores within the body. Platinum in a spongy state absorbs hydrogen gas so powerfully that if a small piece is placed in an escaping jet of hydrogen, the heat developed by the condensation is enough to ignite the jet. This has been made use of in self-lighting Welsbach mantles.

A familiar example of the absorption of gases by liquids and solids is the contamination of milk and butter by onions, fish, or other kinds of food, if they are kept in the same compartment of a refrigerator. Onions, for instance, give off a small quantity of gas which we can easily detect by our sense of smell, or by the watering of our eyes. This gas, when absorbed by milk or butter, affects its taste.

106. Diffusion of gases. The diffusion of hydrogen through a porous cup is shown in the following experiment.

If we set up a porous cup with a stopper and glass tube, as shown in figure 134, and allow hydrogen (or illuminating gas) to fill the jar which surrounds the porous cup, we observe bubbles rising from the end of the glass tube, which dips under water. This means that the gas is going through the porous walls of the cup and forcing the air out at the bottom. If we now shut off the gas and remove the jar, we presently see the water slowly rising in the tube; this shows that the gas inside the cup is going out.

The fact that a little ammonia (or any other gas with a powerful odor) introduced into a room is soon perceptible in

every part of the room shows that the gas particles travel quickly across the room. Moreover, this mixing of gases goes on, whatever the relative densities of the gases; so that a heavy gas like carbon dioxide and a light gas like hydrogen will not remain in layers like mercury and water, but will quickly diffuse and become a homogeneous mixture. Experiments show that the smaller the density of the gas, the greater the velocity of its diffusion. This is the basis of a process recently proposed for separating helium from natural gas by successive selective diffusions.

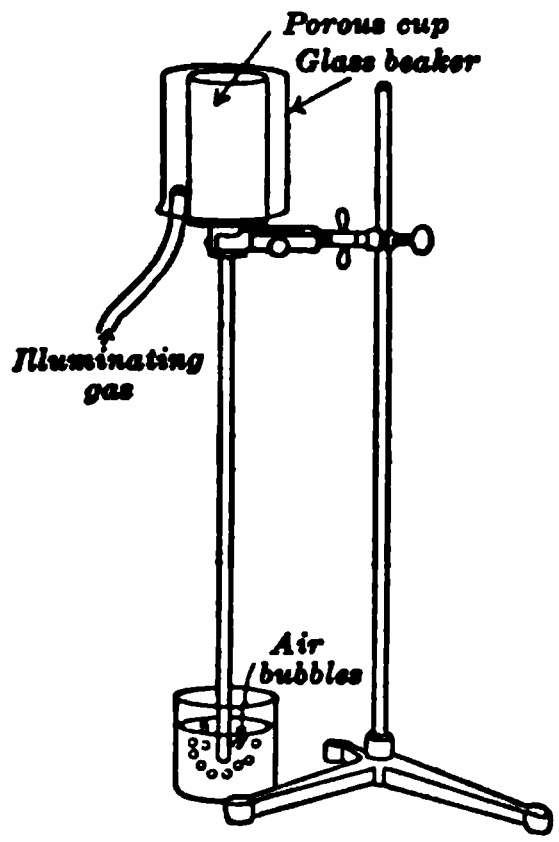

Fig. 134. Diffusion of hydrogen through porous cup.

107. Molecular theory of gases. To explain the pressure of gases and their diffusion, it is now generally believed that all substances consist of very minute particles called **molecules.** These molecules are so minute that we cannot see them even with the most powerful microscopes. In one cubic centimeter of a gas there are not less than 25×10^{18} (that is, 25 followed by 18 ciphers) molecules. The spaces between the molecules are much larger than the molecules themselves. This explains why gases are so easily compressed and diffuse so quickly.

Then, too, these little particles are flying about in all directions with great velocity. They travel in straight lines except when they hit each other and bounce off. Gas molecules seem to have no inherent tendency to stay in one place, as do the molecules of solids. This explains why gases fill the whole interior of a containing vessel. This also explains gas pressures, for the blows which the innumerable molecules of a gas strike against the surrounding walls constitute a continuous force tending to push out these walls. When a

gas is compressed to half its volume, the pressure is doubled, because doubling the density doubles the number of blows struck per second against the walls. It has even been possible to calculate the molecular velocity necessary to produce this outward pressure. It appears that the molecules of gases under ordinary conditions are traveling at speeds between 1 and 7 miles per second. The speed of a cannon ball is seldom greater than one half a mile per second.

This, in brief, is the so-called **kinetic theory of gases.**

SUMMARY OF PRINCIPLES IN CHAPTER IV

Atmospheric pressure is equal to about

30 inches of mercury,
34 feet of water,
15 pounds per square inch,
1 kilogram per square centimeter.

Lifting effect of air is equal to *weight of air displaced.*

Total lift of a balloon equals difference between weight of gas and weight of air displaced.

Pascal's Law of Transmission of Pressure: For gases under pressure, the *pressure* is transmitted undiminished in all directions; the *force* varies as the area.

Boyle's Law: At constant temperature the *volume* of a gas varies *inversely* as the *pressure.*
The *density* of a gas varies *directly* as the *pressure.*

QUESTIONS

1. How much of a vacuum can one suck with one's mouth? How hard can one blow?

2. How and why can a glass of water be inverted with the aid of a card without spilling the water?

3. What would be the result of putting a mercurial barometer under a tall bell glass on a vacuum pump?

4. What would be the effect of lengthening the long arm of a siphon?

5. A boat lying on a beach is full of water. How could you empty it with the help of a suitable length of hose? Could you use the same method to get the bilge water out of a boat floating in the water?

6. Figure 135 shows a gauge which may be attached to the tube of an automobile or bicycle tire to measure the pressure of the compressed air. Explain its operation.

7. Explain why the liquid does not run out of a medicine dropper.

8. Explain the action of a drinking fountain (Fig. 136).

9. A man finds that vinegar does not flow out of a barrel until he removes the bung. Explain.

10. A vessel one meter deep is filled with mercury. Can it be entirely emptied by means of a siphon?

11. Why does a man in a diving suit under water have to be supplied with *compressed* air?

Fig. 135. Pressure gauge used for automobile tires.

12. What advantages has compressed air over electricity for the transmission of power?

13. If the area of a man's body is 20 square feet, what is the total force exerted on him by the atmosphere? Why is he not crushed by this force?

14. In building tunnels workmen usually have to work in chambers filled with compressed air. Why is this necessary?

15. What facts indicate that the atmosphere becomes rarer and rarer as one rises above sea level?

16. How can a balloon be made to sink or rise?

Fig. 136. Drinking fountain.

17. If a balloon is full of hydrogen when it leaves the ground, why does it not burst when it rises into a region of lowered atmospheric pressure?

18. Why does a trailing drag-rope make it easier to land a free balloon gently?

19. How does a gas meter (Fig. 137) work?

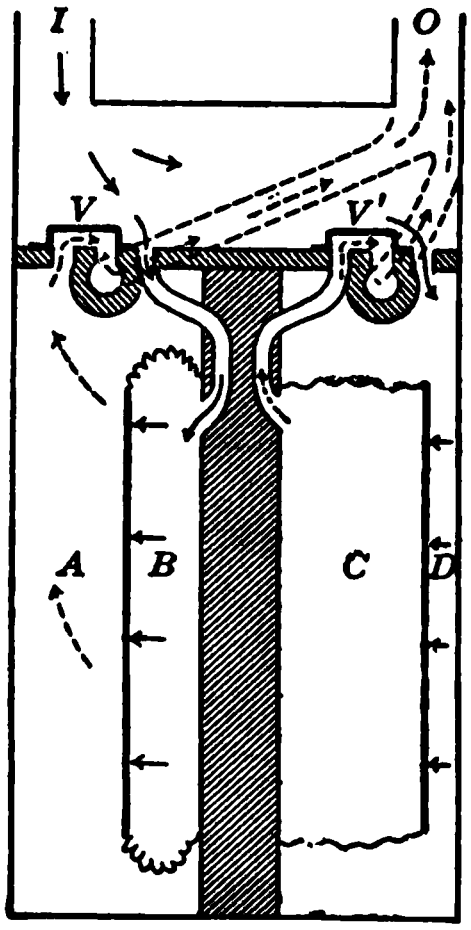

Fig. 137. Diagram of a gas meter.

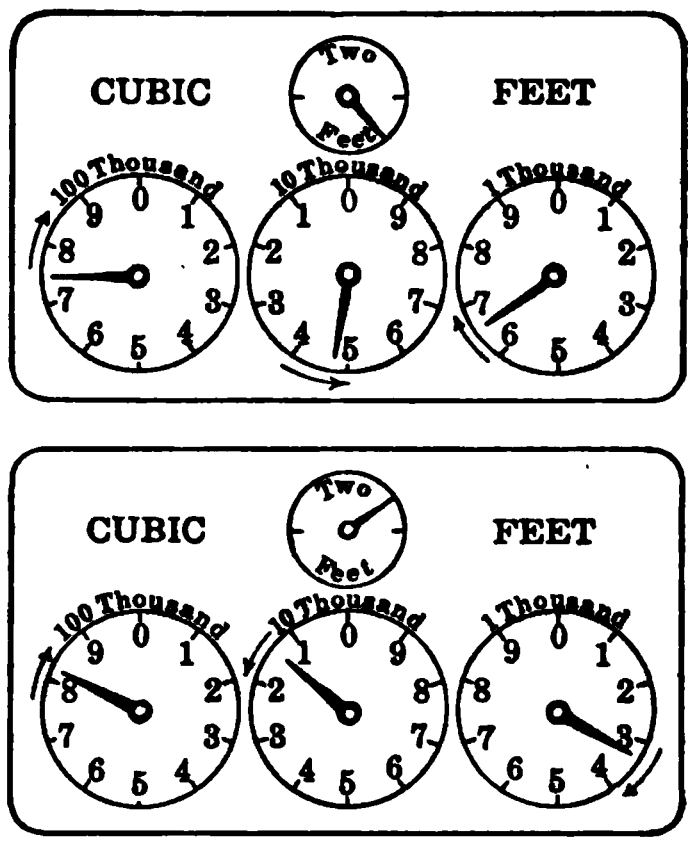

Fig. 138. Dials on a gas meter.

20. Figure 138 represents the dials on a gas meter at the beginning and at the end of the month. (*a*) What is the purpose of the small dial marked Two Feet? (*b*) If gas costs $1.25 per 1000 cubic feet, what is the amount of the bill for the month? (*c*) Draw a diagram to represent 84,600 cubic feet.

21. Would it make any difference in the gas bill if the meter were in the attic instead of in the cellar? In apartment houses with a separate meter for each apartment, do the people on the top floor get more or less gas for their money?

22. A city gas plant stands in a valley and a gas main runs from it to a house high on a hill above it. Will the gas pressure in the main, as measured by a manometer (Fig. 131), be greater at the gas works or at the house? Why?

CHAPTER V

NON-PARALLEL FORCES

Representation of forces by arrows — the parallelogram of forces — composition and resolution of forces — finding coefficient of friction — application to roof truss, sailboat, and airplane.

108. Three forces acting at a point. In machines and other contrivances it often happens that forces which are not parallel balance each other and are thus in equilibrium. For example, suppose a street lamp is suspended over a street by a wire stretched between two posts, as shown in figure 139. We have here three non-parallel forces in equilibrium: first, the vertical pull OW due to the weight of the lamp; second, the pull exerted by one of the ropes OA; and third, the pull exerted by the other rope OB. We are now to find what relation must exist between the magnitude and direction of any three such forces, in order that they may produce equilibrium.

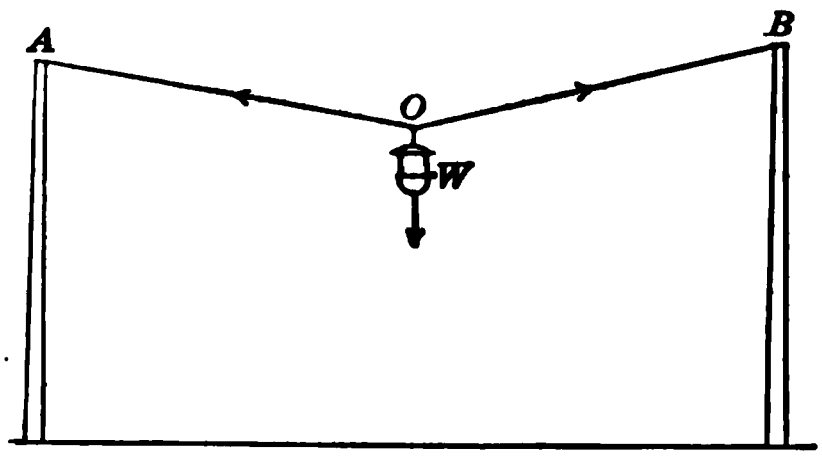

Fig. 139. Three non-parallel forces.

109. Representation of forces by arrows. It will help us to form a mental picture of these three forces if we represent each of them by an arrow. The *direction* of each force will be indicated by the direction of the arrow, the *point of application* by the tail of the arrow, and the *magnitude* of the force by the length of the arrow, drawn to some convenient scale.

Thus, in figure 140 we have an arrow 3 units long, and if we assume that each unit represents 10 pounds, the arrow OX represents a force of 30 pounds applied at O, acting due east. Figure 141 represents two forces, one OX of 30 pounds, acting due east applied at O, and the other OY of 40 pounds, acting due north, applied at the same point O.

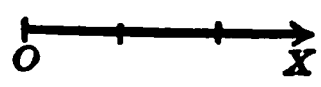

Fig. 140. A force of 30 pounds acting east.

If these two forces act simultaneously upon the body at O, the result will be the same as if a single force were applied, acting somewhere between OX and OY, but nearer the greater force OY. *This single force OR, which produces the same result as two forces OX and OY, is called their resultant.*

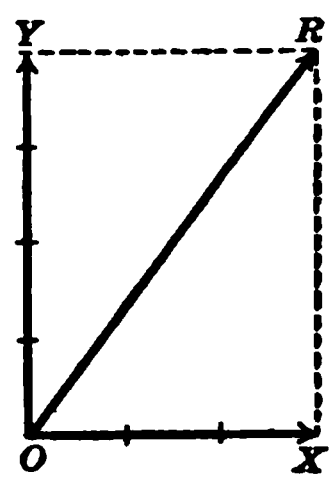

Fig. 141. Resultant of two forces at right angles.

110. Principle of parallelogram of forces. If a parallelogram is constructed on OX and OY, the diagonal OR represents the resultant. This can be illustrated by the following experiment.

Suppose we hang two spring balances A and B from two nails in the molding at the top of a blackboard, as shown in figure 142, and tie some known weight W near the middle of a string joining the hooks of the two balances. If we draw a line on the blackboard behind each of the three strings, we shall have represented the direction of each of the three forces. Then we note the tension in each string, as shown by the amount of the weight W and the readings of the spring balances A and B, remove the apparatus, and complete the diagram. Choosing some convenient scale, we measure off

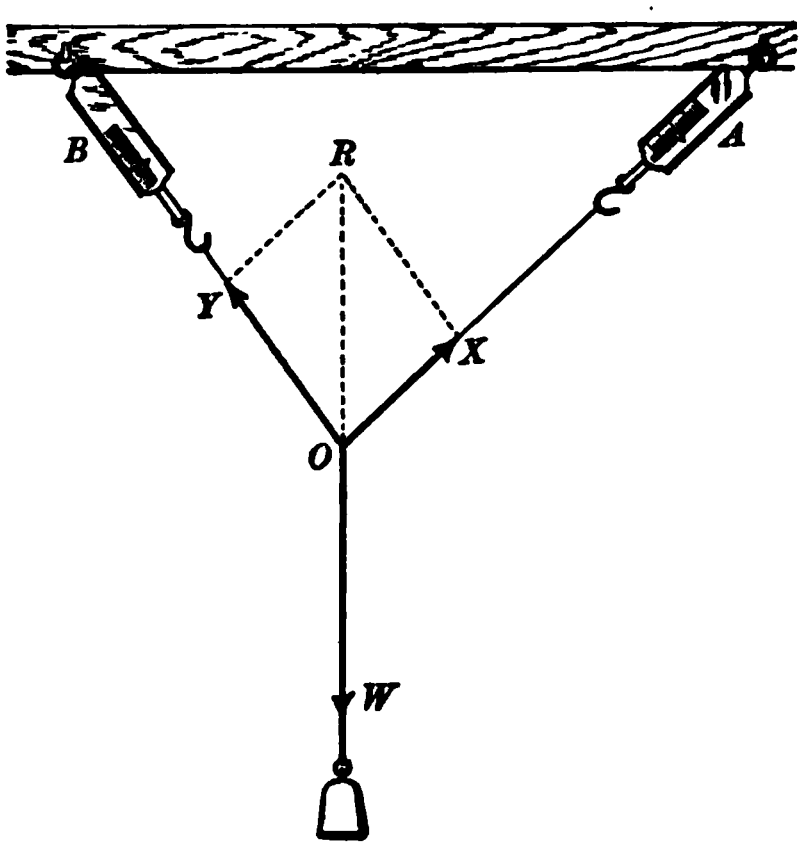

Fig. 142. Experiment to illustrate parallelogram law.

on OA a distance corresponding to the tension in OA, and place an arrowhead at X; in the same way we locate Y on OB. Then we construct a parallelogram on OX and OY by drawing XR parallel to OY and YR parallel to OX. It is evident that the diagonal OR is the resultant of OX and OY, for if we measure OR and determine its magnitude from our scale of force, we find that *this resultant OR is almost exactly equal and opposite to the third force OW*. That is, OW is balanced by OR or by OX and OY.

The force necessary to balance, or hold in equilibrium, two forces is called the **equilibrant**. Thus, in the case just described, the force OW is the equilibrant of the two forces OX and OY.

The resultant of two forces acting at any angle may be represented by the diagonal of a parallelogram constructed on two arrows representing the two forces.

When three forces are in equilibrium, the resultant of any two of the forces is equal and opposite to the third, which can be regarded as their equilibrant.

111. Resultant depends on the angle between forces. To determine the resultant of two or more forces, we must know

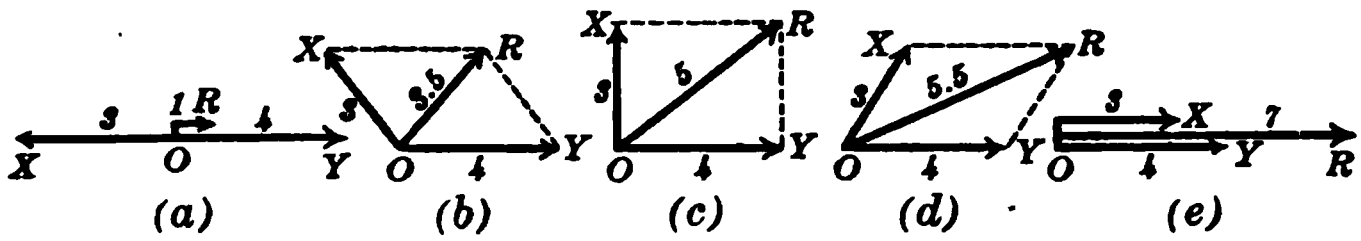

Fig. 143. Two forces at varying angles.

not only their magnitudes, but also the angle between them. This will be made clear by studying the same two forces at different angles, as in figure 143. It will be seen that the resultant OR gradually increases as the angle between the forces OX and OY decreases from 180° to 0°.

For example, if the angle is 180° as in (*a*), the forces OX and OY are opposite, and the resultant is the difference between the forces, $4 - 3$, or 1, and acts in the direction of the greater force, *i.e.* toward the right. As the angle gradually decreases the resultant OR increases, until,

when the angle is 0° as in (*e*), the forces OX and OY are acting in the same straight line and in the same direction, and the resultant is the sum of the two forces, $4 + 3$, or 7. When the forces are at right angles as in (*c*), the resultant can be computed from the geometrical proposition about the sides of a right triangle, namely, *the square on the hypothenuse is equal to the sum of the squares on the two sides.*

Thus,
$$\overline{OR}^2 = \overline{OX}^2 + \overline{OY}^2$$
$$\overline{OR}^2 = 3^2 + 4^2 = 25$$
$$OR = 5.$$

For oblique angles, such as (*b*) and (*d*) in figure 143, the resultant can be determined by plotting the forces to scale, or by trigonometry.

The process of finding the resultant of two or more component forces is called the **composition of forces.**

112. Illustrative examples of composition of forces. Suppose we have a crane arm AB attached to a wall as shown in figure 144 (*a*). The weight W is 2000 pounds and the tension in the cable AC is 1500 pounds. What is the force exerted by AB? In the solution of such problems it will be found helpful to draw a **force diagram** (Fig. 144 (*b*)), where AW represents the pull of the weight W, AC the pull of the cable, and AE the thrust of the crane arm. As these three forces are in equilibrium, we can apply the principle of the parallelogram of forces. We want to find AR, the resultant of AC and AW. Since AC and AW form a right angle, we know that

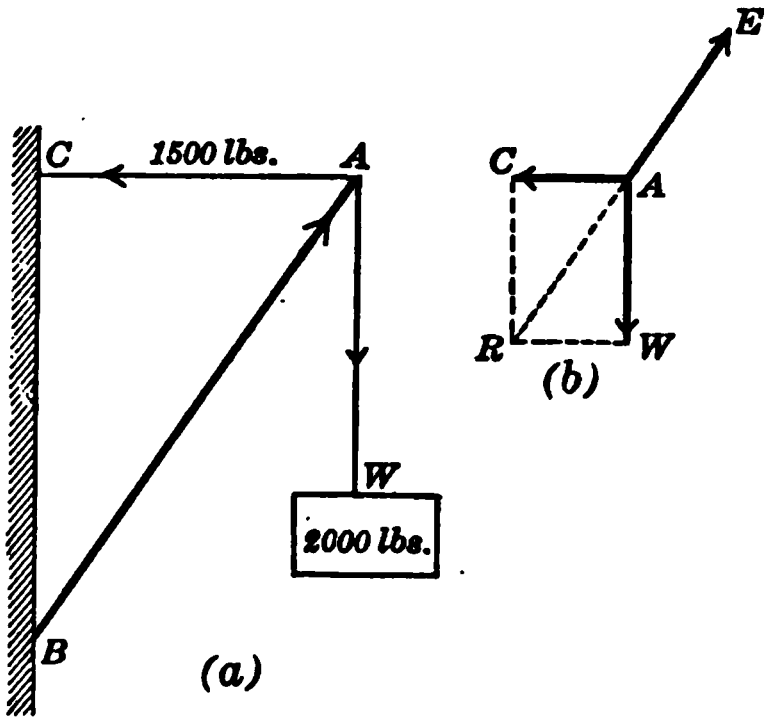

Fig. 144. Three forces acting on a crane.

$$\overline{AR}^2 = \overline{AC}^2 + \overline{AW}^2 = \overline{1500}^2 + \overline{2000}^2$$

or
$$AE = 2500 \text{ pounds.}$$

Therefore the push exerted by AB is 2500 pounds.

Again, suppose we have a 100-pound child in a swing (Fig. 145). A man pushes the child to one side with a force of 20 pounds. What are the magnitude and direction of the pull exerted by the rope? In the force diagram (Fig. 145), CW represents the weight of the child (100 pounds), CP represents the push (20 pounds) of the man against the child, and CR represents the pull of the rope which we wish to determine. The resultant CR' of CP and CW is equal to $\sqrt{CP^2 + CW^2}$, or $\sqrt{(20)^2 + (100)^2}$, or about 102 pounds. Therefore the tension in the rope is also 102 pounds. Its direction can be found from the diagram.

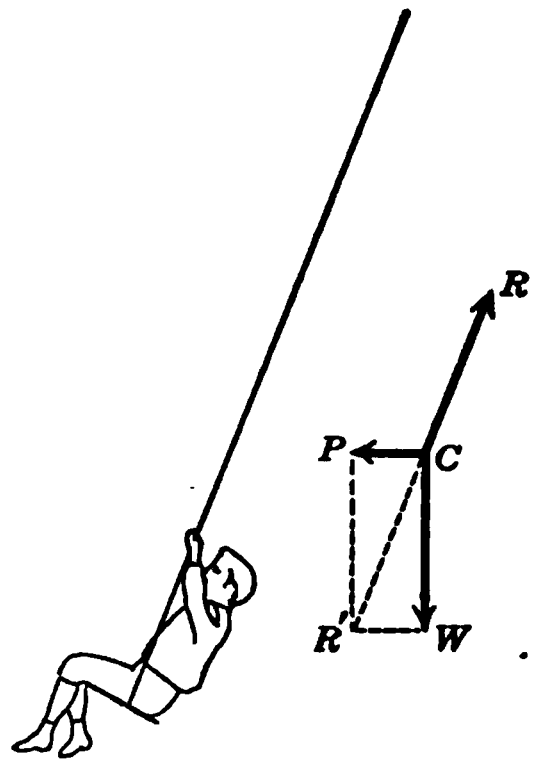

Fig. 145. Three forces acting on child in swing.

PROBLEMS

(In the following problems first solve by plotting on as large a scale as possible and then by computation.)

1. Find the resultant of a force of 8 pounds toward the east and one of 4 pounds toward the north.

2. A force of 100 pounds acts north and an equal force acts west. What is the direction and magnitude of the equilibrant?

3. Find the resultant of a force of 10 pounds east and one of 14.1 pounds southwest.

4. Two 100-pound forces act at an angle of 60° with each other. Find their resultant.

5. Find the resultant of two 100-pound forces which act at an angle of 120° with each other.

6. Two forces, 5 pounds and 12 pounds, act at the same point. Find their equilibrant, (*a*) if they act in the same direction; (*b*) if they act in opposite directions; and (*c*) if they act at right angles.

7. Find the resultant of three forces: A 10 pounds north, B 15 pounds south, and C 12 pounds west. (First find the resultant of A and B and then the resultant of this resultant and C.)

113. Resolution of forces. The principle of the composition of forces can be worked backward. If one force is given,

we can find two others in given directions which will balance it. For example, take the case of the lamp suspended above the middle of the street (Fig. 139). If we know the weight of the lamp and the angle of sag of the ropes, we can calculate the tension in the ropes.

FOR EXAMPLE, suppose that the weight of the lamp is 50 pounds, and that the rope ALB (Fig. 146) sags so as to make both the angle ALR and the angle BLR equal to 75°. In the diagram draw the arrow LW down from L to represent 50 pounds on some convenient scale. As the two ropes have to hold up the lamp, the resultant of the forces representing the tension in the ropes must be equal and opposite to the force representing the weight.

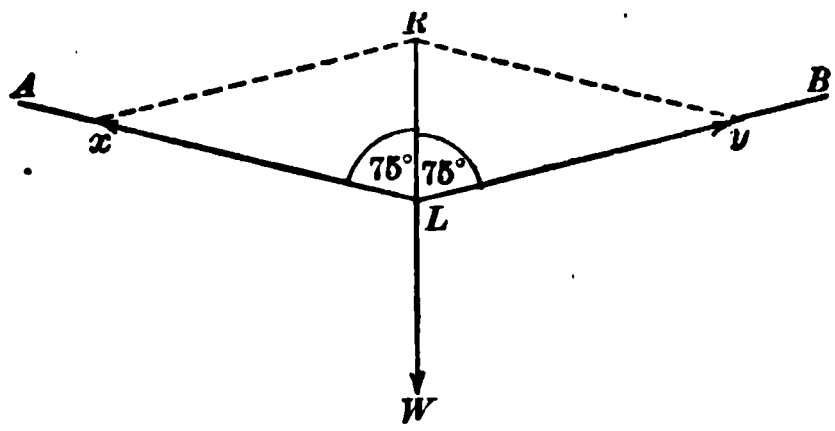

Fig. 146. Diagram of three forces acting on street lamp.

So we draw LR equal and opposite to LW. Then we construct a parallelogram on LR as a diagonal with its sides parallel to LA and LB, Ry being drawn parallel to LA, and Rx parallel to LB. Ly represents the tension in the rope LB and is found by measurement to be equal to about 96.6 pounds, and Lx represents the tension in LA and is also equal to about 96.6 pounds.

Another good example of the resolution of one force into two forces which just balance it is the case of a street lamp hung out on a bracket from a pole, as shown in figure 147 (a).

FOR EXAMPLE, suppose the lamp L, weighing 50 pounds, is hung out from a pole PC by means of a stiff rod AB, 10 feet long, and a tie rope or wire BC, which is fastened to the pole at C, 3 feet above A. What is the force exerted by the rope BC?

In the diagram (Fig. 147 (b)), the weight of the lamp is represented by OW, the push of the rod AB by OP, and the tension of the tie rope BC by OT. Since we know the force OW (50 pounds), we draw this line to some convenient scale. The resultant of OP and OT must be equal and opposite to OW. Therefore we make OR equal and opposite to OW. Then, completing a parallelogram on OR as a diagonal, we have OP representing the push of the rod against the lamp, and OT the

tension in the tie rope *BC*. If we draw these lines carefully to scale, we find that the tension is 174 pounds. How much is the push *OP*?

In general, a single force may be resolved into two forces acting in given directions, by constructing a parallelogram whose

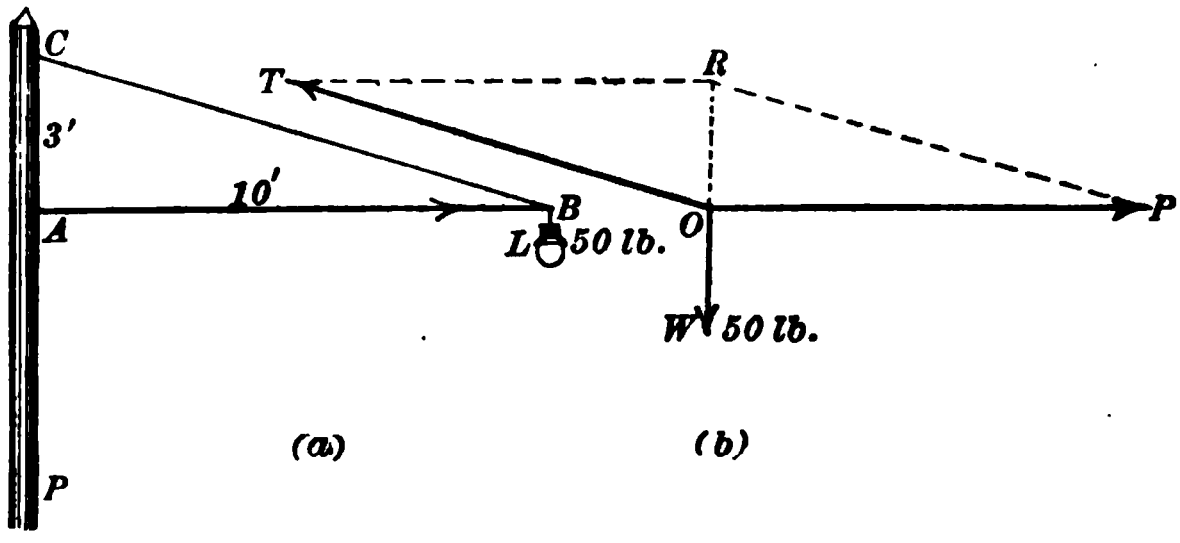

Fig. 147. Three forces acting on lamp hung in bracket.

diagonal represents the given force, and whose sides have the given directions.

114. Component of a force in a given direction. If a force is given, we can find two other forces, one of which represents the **whole effect in a given direction** of the given force.

Thus in figure 148 we have a canal boat *AB* which is being towed by the rope *BC*. We may resolve the force along

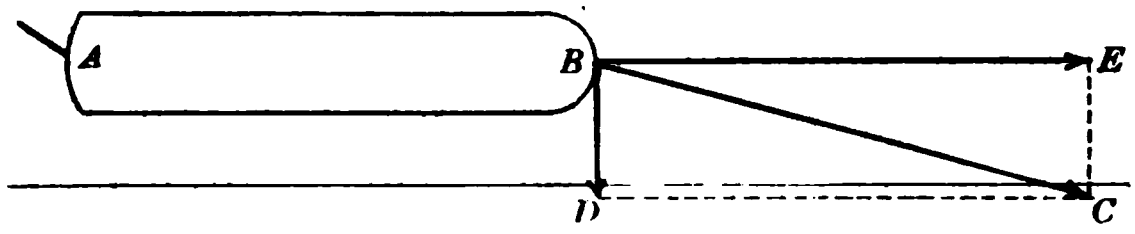

Fig. 148. Useful component of force acting on canal boat.

the rope *BC* into two forces, one of which, *BE*, is effective in pulling the boat along the canal, and the other, *BD*, at right angles, is useless or worse than useless, since it tends to pull the boat toward the bank. *BE*, the **useful component** of *BC*, can be computed by drawing the force *BC* to scale and then constructing a **rectangle** on *BC* as a diagonal, such as *BECD*.

115. Hints on solving practical problems. The principle of the parallelogram of forces is one of the foundation stones in the study of mechanics. When stated with the aid of a geometrical diagram, it seems simple, but when met with in a crane, derrick, bridge, or roof truss, it is puzzling. This is because, in solving practical problems, we seldom find bodies which are small enough to be regarded as points at which forces act. Nevertheless we can solve problems by this method, even when the bodies are large. For if any body is held still by three forces, their lines of action, if prolonged, must go through a single point, as shown in (*a*), figure 149. If this were not true of three forces acting on a body (Fig. 120 (*b*)), it would *spin* around. So we can think of the forces as acting at a single point, even though the body in which the point lies is large.

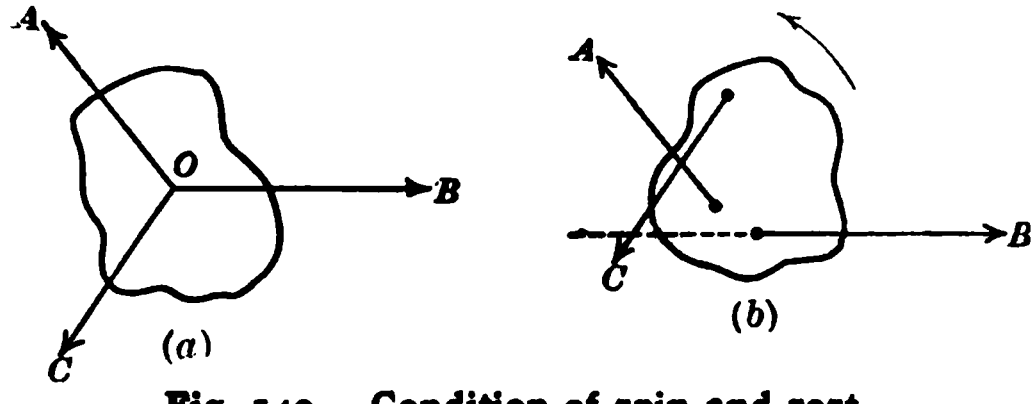

Fig. 149. Condition of spin and rest.

Another difficulty in solving practical problems is the failure to visualize all the forces (pushes or pulls) acting on any body. A beam may be pushing or a rod may be pulling, even though it does not move. Experience shows that it is helpful to draw two diagrams, side by side. One should be a sketch of the body by itself, **isolated** from its surroundings. This sketch should show dimensions, angles, and the directions and points of application of *all* the forces acting *on* the body. Do *not* consider any forces which the body may itself be exerting on anything else. Also, do not forget the weight of the body. The second diagram shows only the forces themselves, each represented by an arrow drawn to scale starting from a common origin, and such construction lines as may be necessary to form the needed parallelograms and resultants.

Applications of the Parallelogram of Forces

116. Friction on an inclined plane. When an object is placed on an inclined plane, friction tends to keep the object from sliding down the plane (Fig. 150). If the angle of inclination is small enough, this friction will prevent the object from sliding down the plane.

For example, suppose an electric car is on a grade with the brakes set so that the car stands still. How steep can the grade be before the car slides down? In the diagram, figure 150, let OW represent the weight of the car, OP the pressure of the inclined plane against the car, and OF the friction which retards its motion. When these three forces are in equilibrium, the resultant of OP and OW, that is, OR, must be opposed by an equal force OF. Now OF can never exceed a limiting value which depends on the pressure and on the coefficient of friction, the latter being determined by the condition of the track. But the resultant OR increases as the incline becomes steeper. So, as the steepness increases, we soon reach a condition in which OR is greater than OF possibly can be, and the car slides down. If we know the coefficient of friction between the wheels and the rails, we can compute the grade at which the car will begin to slide.

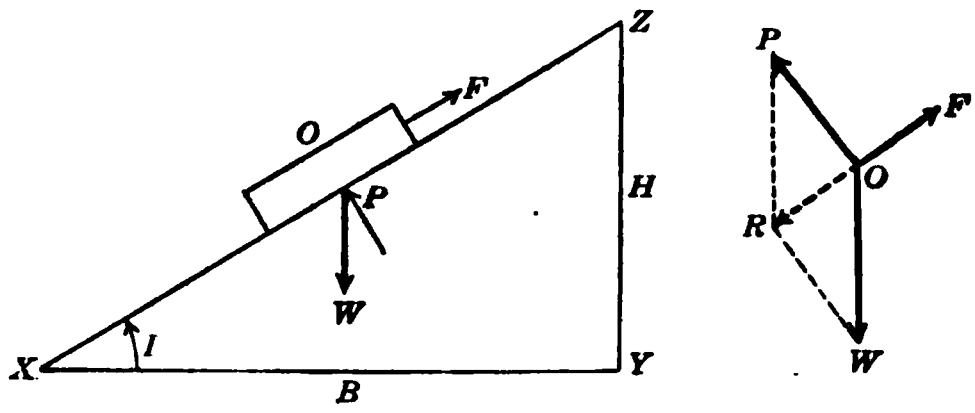

Fig. 150. Friction on inclined plane.

Let figure 150 represent this grade. We have already (section 52) defined the coefficient of friction as the ratio between friction and pressure, and so, in this case, we have

$$\text{Coefficient of friction} = \frac{OF}{OP} = \frac{OR}{OP}.$$

From geometry we know that the triangles OPR and XYZ are similar since they are mutually equiangular. It follows that

$$\frac{OR}{OP} = \frac{H}{B} = \frac{\text{height of plane}}{\text{base of plane}}.$$

Therefore

$$\textbf{Coefficient of friction} = \frac{\textbf{height of plane}}{\textbf{base of plane}}$$

This is a convenient way of measuring coefficients of friction.

Problems

(Solve these problems by means of large, carefully made diagrams, and check your answers, whenever you can, by computation.)

1. Given a force of 100 pounds acting north. Resolve this into two forces, one acting northeast and the other northwest.

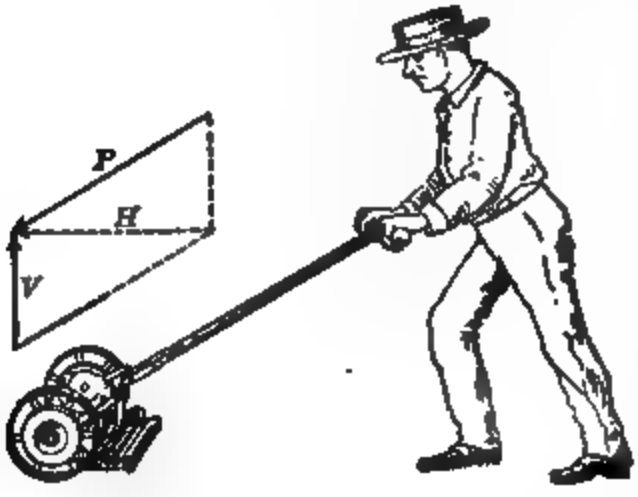

Fig. 151. Useful component of push against lawn mower.

2. Given a force of 100 pounds acting north. Resolve this into two forces, one acting northwest and the other east.

3. Given a force of 100 pounds acting north. Resolve this into two forces acting at right angles with each other, one of which shall be twice as great as the other.

4. A man pushes on a lawn mower (Fig. 151) with a force of 60 pounds along the handle, which is tilted at an angle of 30° from the ground. (*a*) What is the useful component of this force? (*b*) If the handle is tilted at an angle of 45°, what is the useful component?

5. A 200-pound barrel of flour is held in place on a skid (Fig. 152). If the skid is so tilted as to make an angle of 30° with the ground, (*a*) what force must a man exert parallel to the incline? (*b*) What force does the skid exert (perpendicularly) on the barrel?

Fig. 152. Forces applied to barrel on skid.

117. Roof truss. When a wooden house is built, the roof is usually supported by pairs of timbers set like an inverted V, as in figure 153. Each pair of timbers has to carry the weight of a section of the roof, and, in winter, of the snow and ice that accumulate on it. This weight is really dis-

tributed along the timbers; but it can be thought of as concentrated, half at the peak and half at the eaves, where it rests directly on the walls. The part of the load that is at the peak tends to "spread" the inverted V, and our problem is to find what has to be done to prevent this.

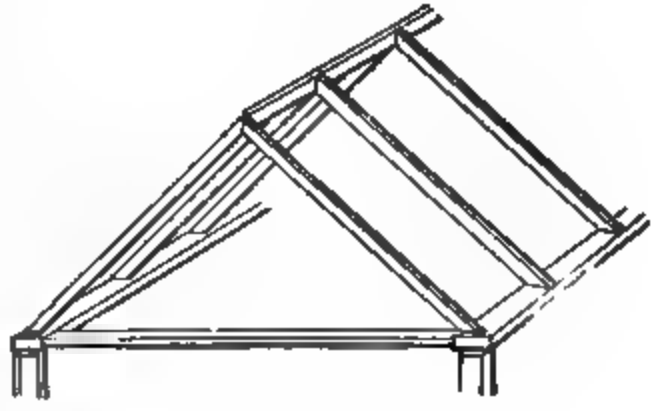

Fig. 153. Roof trusses.

We may test this experimentally with a small model of a pair of roof trusses (Fig. 154). These have hinges at the top instead of a stiff joint, and frictionless wheels underneath, so that they will not stand up at all under the load W unless *a tie is put across the bottom of the* Λ *to prevent the spreading.* If a spring balance is put into the tie, the pull which the tie has to exert on the truss members can be measured. If the load at

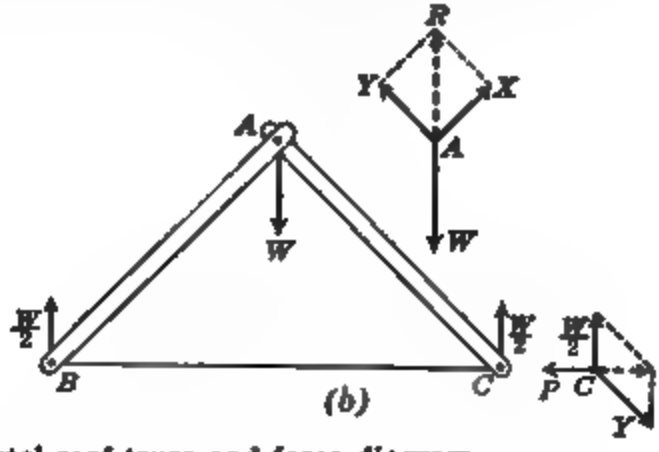

Fig. 154. Experimental roof truss and force diagram.

the peak is 50 pounds, and if the truss members make a right angle, the "tension" in the tie will be about 25 pounds.

In discussing this experiment, we have to apply the parallelogram of forces at two points successively. In the first place, let us consider the pin A of the hinge at the top. This is acted on by three forces, the pull of the weight AW, and the push exerted by each rod AB and AC (Fig. 154 (*b*)). Since these balance, we can find each push by constructing a parallelogram whose diagonal is equal and opposite to AW. If the rods are at right angles, this parallelogram is a square, and the pushes are equal. Let each push $= x$, then $2x^2 = 50^2$, or $x = 35.3$ pounds.

Turning next to the pin at the foot of one rod, we see that it is also acted on by three forces, the push of the rod, 35.3 pounds, the upward push exerted by the table which is $\frac{1}{2}W$ (half the weight), and the pull of the tie wire. Since these balance, we can get the last by constructing the diagonal of a parallelogram on the known forces. This parallelogram is composed of two 45° triangles, and so the pull of the tie wire equals the push of the table, or 25 pounds.

In building a roof, the pull exerted by the tie wire in our experiment has to be provided for in some way. Usually the ends of the roof timbers are nailed to the frame of the building, which is stiff enough to exert a part or all of the

Fig. 155. Framed bridge with pinned joints.

required force. Often a board is nailed across the inverted V, either at the bottom or a little higher up, to help exert it. In large roof trusses, as in churches, an iron rod is strung across and tightened with a screw coupling.

118. Bridges. Large bridges are built of wood or steel "members" joined to form a number of adjacent triangles. If the members are strong enough not to stretch, shorten, or buckle under the loads imposed on them, each triangle, having three sides of unchanging length, keeps its shape, and so the whole truss is rigid.

In very large bridges the members are joined together at the corners of the triangles by boring holes in them and thrusting a steel pin through all the holes at a joint. Bridges made in this way are called **pinned bridges** (see Fig. 155). In designing a pinned bridge, an engineer computes the "stresses in the members," that is, the forces which they have to exert to hold the bridge stiff under load, by applying the parallelogram of forces to the pin at each joint successively. The members which have to push against the pins at their ends are called **compression members**, because they tend to shorten under load; while those that have to pull on the pins at their ends are **tension members**, and tend to lengthen under load. In large bridges it is easy to see which are compression members and which tension, for the compression members are made broad and stiff with "latticing" up their sides, while the tension members are steel straps or rods with enlarged ends to give room for the holes. Thus the heavy lines in figure 156 indicate compression members, while the light lines correspond to tension members.

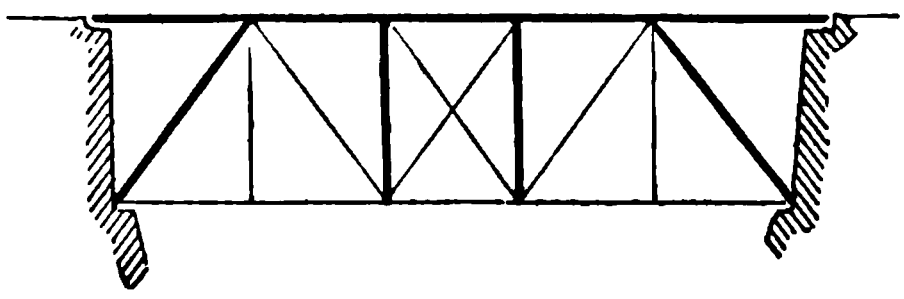

Fig. 156. Diagram of the bridge shown in figure 155.

In smaller bridges the members are not joined by pins, but are riveted to "gusset plates" at each joint. Such bridges are designed as if they were pinned, the stiff joints giving an additional factor of safety.

The smallest steel bridges are supported by **plate girders**, one on each side, which are simply stiff steel beams. Roofs of large span are often supported by framed trusses, made of members forming triangles, like bridge trusses.

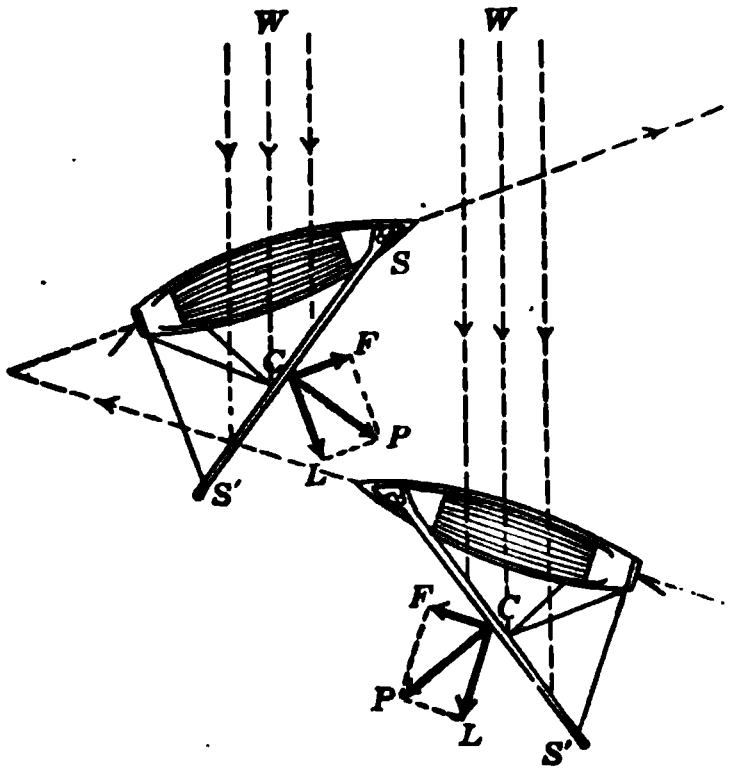

Fig. 157. How a boat sails into the wind.

119. How a boat sails into the wind. Let figure 157 represent a boat, SS' its sail, and W the wind. It is sometimes hard to see how such a wind pushes the boat ahead instead

of forcing it backward. The wind blowing against the slanting sail SS' is deflected and causes a force perpendicular to the surface. This force can be represented by the arrow CP in the diagram. The force CP can be resolved into two components: one useful, CF, which points forward parallel to the keel of the boat; and the other useless, CL, which tends to move the boat to leeward. This sidewise movement is largely prevented by a deep keel or a centerboard. So the net effect of the wind is to drive the boat forward.

120. Airplanes and seaplanes. The "first successful power flight in the history of the world" was made on the morning

Fig. 158. Front view of the Martin mail-carrying biplane with two motors.

of December 17, 1903, by the Wright brothers. Since that date, the flying machine has been so perfected as to become a powerful weapon in war, a valuable scouting machine for locating forest fires and schools of fish at sea, and an increasingly useful means of commercial transportation. Mails go by airplane, and there is a network of regular daily air services all over Europe, those between London and Paris carrying over 1000 passengers in a single month in 1921.

The **biplane** (Fig. 158) is the prevailing type; it has two wings set one above the other. Each wing is long and narrow

and moves with its long edge forward, as this shape and aspect have been found to give much more lift per square foot than any other. Large **monoplanes**, with a single wing on each side of the body, are apparently the coming type. Their wings are thick enough to allow internal bracing exclusively and are sometimes covered with thin sheets of metal instead of the prevailing cloth fabric.

The propellers are driven by light but very powerful gasoline engines, such as the American Liberty motor (Fig. 159), either

Fig. 159. The Liberty motor was developed during the World War. It weighs 806 pounds and is rated at 400 horse power.

directly or through speed-reducing gears. In the smaller planes there is one propeller, usually in front, where it *pulls* the plane along. The larger planes have two, three, or even four engines, each driving a propeller.

Airplanes have two or more wheels underneath so that they

can "take off" from, and land on, any large, smooth piece of ground. **Seaplanes** (Fig. 161) have water-tight boat-shaped bodies which enable them to take off from, and land on, the water. Usually there is also a smaller pontoon or float underneath each tip of the lower wing to balance the plane when it is not flying.

121. What supports an airplane. A balloon rises because it and its gaseous filling weigh a little less than the air displaced. An airplane is, however, much heavier than the air it displaces, and is kept up only by the upward pressure of the air against its wings.

The action is much like that of a kite floating in a wind. The moving air strikes against the lower, inclined surface of the kite and is deflected downward, exerting a force nearly normal to the face of the kite. This force and the pull of the kite string are such as to have a resultant pointing straight up, that exactly balances the weight of the kite.

Fig. 160. Forces acting on an airplane.

In the case of the airplane there is also a rush of air past the wings, although it is due to the motion of the airplane itself through the air, rather than to a wind, as in the case of the kite. This rush of air is deflected downward and gives a thrust OP, as shown in figure 160, against and nearly perpendicular to the wing surface. There is also the forward thrust OF of the propeller, which corresponds in a way to the pull of the kite string. Just as in the case of the kite, these two forces have a resultant OR, which points straight up and balances the weight OW of the airplane. If the propeller speed increases, then the forward thrust OF and the push OP of the air against the wings increase. Consequently the upward resultant force OR is greater than the weight, and the airplane rises.

Fig. 161. The U. S. Navy seaplane *NC-4* which completed the first transatlantic flight on May 31, 1919. The total distance, 4513 miles, was made with five stops on the way. This biplane was equipped with three Liberty motors. Its total weight loaded was about 14 tons and its total wingspread 126 feet.

PROBLEMS

1. Figure 162 shows a simple crane. Find the tension in the tie rope BC and the push of the brace AC, when the weight W is one ton, and the angle BAC is 45°. Neglect the weight of the brace.

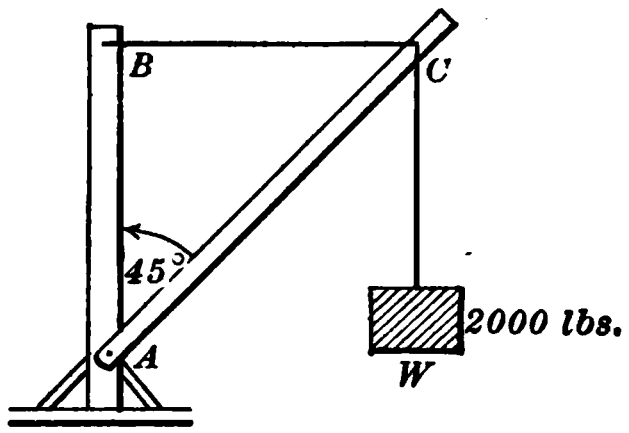

Fig. 162. Diagram of a simple crane.

2. In figure 148 the point B of the canal boat is 10 feet from the tow-path, and a pull of 200 pounds is exerted on the 50-foot towline. What is the effective component?

3. A boy weighing 120 pounds sits in a hammock whose ropes make angles of 30° and 60°, respectively, with the vertical. What is the tension in each rope?

4. Each rope in problem 3 is fastened to a hook in the ceiling. Find the vertical pull on each hook.

5. One end of a horizontal steel girder 10 feet long rests on a ledge in the wall, and the other end is supported by a chain arranged as shown in figure 163. Assuming that the girder weighs 40 pounds per foot, find the tension in the chain.

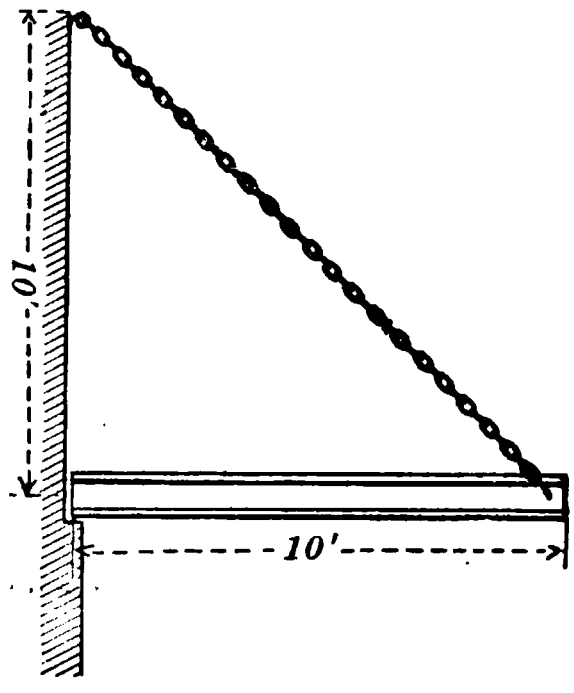

Fig. 163. Girder supported from a wall.

6. If the point where the chain in problem 5 is attached to the wall had been only 5 feet above the girder, what would the tension in the chain have been? Why is the tension in this position so much more than in the position of problem 5?

7. The net lift of a captive balloon is 250 pounds, and it is held by an anchor rope which makes an angle of 60° with the ground. Compute the tension in the anchor rope (assumed to be straight), and the horizontal force exerted by the wind against the balloon.

8. A child weighing 60 pounds is sitting in a swing, the seat of which is 12 feet below the support. (*a*) What horizontal force is required to hold the child 6 feet to the left of the vertical line? (*b*) What is the tension in each rope?

SUMMARY OF PRINCIPLES IN CHAPTER V

Forces can be represented by arrows drawn to scale:

Direction indicated by the arrowhead,
Point of application by the tail,
Magnitude of force by the length.

The parallelogram of forces:

The *resultant* of two forces is the *diagonal* of a parallelogram constructed on arrows representing the two forces.

The *equilibrant* of two forces is equal and opposite to their resultant.

Resolution of forces:

A single force may be resolved into two forces acting in given directions, by constructing a parallelogram whose diagonal represents the given force, and whose sides have the given directions.

If the parallelogram is a *rectangle*, either side represents the *useful* component of the force in that direction.

If three forces act on a body in equilibrium, their lines of action must pass through a single point or be parallel.

QUESTIONS

1. Show by a diagram the useful component of the pull exerted on a sled by a rope.

2. Why is a long towline more effective in hauling a canal boat than a short line?

3. Why does one lower the handle in pushing a lawn mower through tall grass?

4. A boat is rowed across a river. (*a*) What two forces are acting on the boat? (*b*) In what direction should one row in order to land directly opposite?

5. A child sitting in a swing is gradually drawn aside by a force which continually acts in a horizontal direction. Does the tension in the swing rope grow smaller or larger? Explain.

6. Why will a long rope, hanging between two points at the same level, break before it can be pulled tight enough to be straight?

7. Find in some building a roof truss with a steel tie rod to keep it from spreading.

8. How are the walls of Gothic cathedrals strengthened so that they can exert the side thrust necessary to hold up the roof?

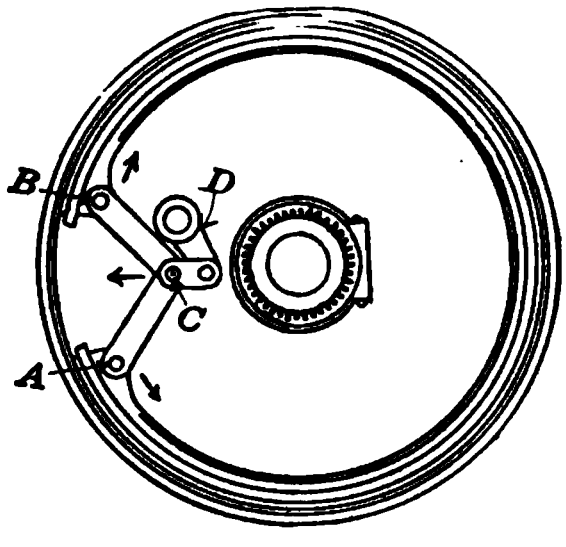

Fig. 164. Toggle-joint used to expand automobile brake.

9. Explain why the **toggle-joint** used to expand an automobile brake (Fig. 164) has such a large mechanical advantage. Draw isolation and force diagrams. Explain how the principle of the toggle-joint may be used in tightening the sail of a cat-boat.

10. Could an ordinary balloon "tack" against the wind like a sailboat if it were provided with a sail, a large keel, and a rudder, like a sailboat? Why?

PRACTICAL EXERCISE

Bridges. Examine the steel bridges in your neighborhood to see if they are "girder bridges" or "framed bridges," and, if any of them are framed, see whether they are pinned or riveted, and which members are compression members, and which tension. Make a sketch like that in figure 156 of one of these bridges, showing the compression members by heavy lines. If possible, make a model bridge of wood and wire. Be careful about loading it near either end. Why?

CHAPTER VI

ELASTICITY AND STRENGTH OF MATERIALS

The different kinds of stress — stress and strain — Hooke's law — elastic limit — breaking strength — commercial testing machines — factor of safety.

122. Importance of studying materials. A structural engineer who is to build a bridge, a building, or a machine must know not only the forces that will be exerted on each of its parts, but also the strength of the wood, brick, stone, concrete, or steel of which they are to be made. This knowledge can be gained only by testing each kind of material with the greatest care. For this reason, every engineering handbook tabulates the results of a great number of tests of this kind. Every large manufacturer of steel girders or rails maintains a testing laboratory so that he can sell his products under a strength guarantee. Even textile manufacturers test the breaking strength of the yarn that goes into their cloth. Indeed, the study of the strength of materials is regarded as of such importance to the public that the government itself maintains a bureau for the purpose. In this chapter we shall learn how such tests are made, and how the results are used.

123. The different kinds of stresses. In designing a beam or column or some part of a machine, an engineer must first know how the force it is to resist will be applied.

For instance, the cable that supports an elevator, or the rope of a swing, or a belt that is transmitting power from one pulley to another *has to resist a pull applied at each end*, which tends to stretch it, and may, perhaps, break it by pulling one part of it away from the next. In such a case we say that the "member" — that is, the cable or rope or belt — is in **tension**, meaning "in a state of tension."

The pier of a bridge, or the foundation of a house, or a post supporting a piazza roof has to do something quite different from this. *It has to resist a push at each end*, which tends to shorten it, and may cause it to give way by crushing it. In such a case we say that the member — that is, the pier or foundation or post — is in **compression**, meaning "in a state of compression."

A floor beam in a house or a girder in a plate-girder bridge is subjected to a transverse stress and has to resist **bending**. If it gives way at all, it does so by breaking in two like a stick broken across one's knee.

The duty of the driving shaft that connects the engine with the rear wheels of an automobile, or of the shafts that run overhead in many factories and transmit power to the various machines, is to resist **twisting**.

And, finally, the duty of a rivet (Fig. 165) in a steel structure is different from any of these. It has to keep one of the plates from sliding over the other. When such a rivet gives way, it is often because the halves of it have been pushed sidewise so hard that one has slid away from the other, leaving a flat, clean break parallel to the surface separating the plates. It is a stress of this sort that we put on a piece of cloth or paper when we cut it with a pair of shears. So we say that the rivet is in **shear**, meaning that it is in the same state as if it were being cut in two by a huge pair of shears.

Fig. 165. Shearing action of plates on rivet.

There are, then, these five kinds of stresses: tension, compression, bending, twisting, and shear. In each case that material and shape should be used which will best resist the particular kind of stress that is to be applied. Thus bricks set in mortar do very well under compression, but are of little use in resisting any of the other kinds of stress. Steel will resist any of them

well. Cast iron will resist compression about four times as well as it will tension, and so on.

124. Stress and strain. Whenever any one of these kinds of stress is applied to a body, the body yields a little. No bridge girder is stiff enough not to bend a little under every truck or train that goes over the bridge. If it is a good girder, the amount of bending is imperceptible to ordinary observation; but there is always some bending. Similarly, every driving shaft in an automobile twists a little when it is transmitting power. The same can be said of the other types of stress; each of them always causes some yielding or deformation of the body under stress.

The word "strain" is used in mechanics to describe the deformation produced. The word **stress** always refers to the forces which are acting, while the word **strain** refers to the effect which they produce.

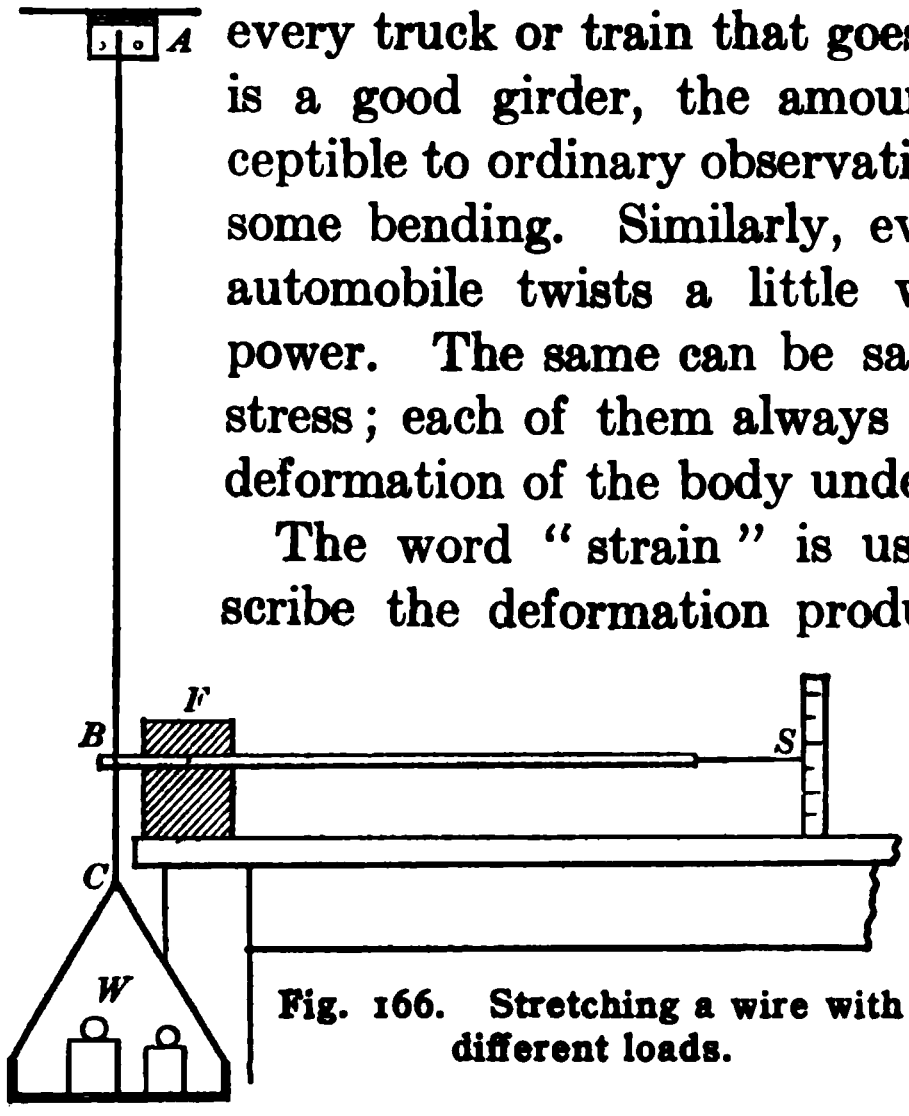

Fig. 166. Stretching a wire with different loads.

125. Relation of strain to stress. Let us try some experiments to see if there is any relation between the amount of stress applied to a body and the amount of strain it produces.

I. ***Tension.*** Let us fasten one end of a piece of steel or spring-brass wire in a clamp near the ceiling, and attach a pan for weights to the lower end of the wire (Fig. 166). Since the stretch will be small, it is necessary to use a lever or some other device to magnify it. Having placed just enough weight in the pan to straighten the wire, we add weights one at a time and read the corresponding positions of the pointer. Each time we must remove the added weights to see if the pointer comes back to its original position. When it fails to do this, we stop the experiment and disregard, for the moment, the last reading of the pointer. If we then compute from each deflection of the pointer the actual stretch, or elongation, of the wire, and divide each

stretch by the force causing it, we find that all the quotients are approximately the same. That is, *the stretch is proportional to the load.*

II. ***Compression.*** The same is true for compression. Thus experiments show that under ordinary conditions *the compression of a spring is proportional to the force applied.*

III. ***Bending.*** We can perform a similar experiment for bending by supporting a metal rod or tube on knife edges, and hanging different weights from the center. A lever, like that used in the tension experiment above, or a micrometer screw enables us to measure the small deflections of the center of the rod. As before, we find that the *deflections are proportional to the loads causing them.*

IV. ***Twisting.*** The apparatus shown in figure 167 enables us to perform similar experiments on twisting. The metal rod is clamped fast at the right-hand end and is clamped at the left in the hub of the wheel. Weights placed in the pan exert a twisting force on the rod, and the amount of twist produced can be read off on the rim of the wheel. As before, we find that *the twist is proportional to the stress causing it*, namely, the *torque*, or moment of the twisting force. Thus, one pound acting at a distance (radius) of one foot exerts a torque of one pound foot.

Fig. 167. Apparatus for twisting metal rods.

In all these cases, *the strain is proportional to the stress.* This is called **Hooke's law**, after the scientist who discovered it. Hooke's law applies to all kinds of strains, if the stresses are not too great.

PROBLEMS

1. If a weight of 1 pound when hung on a certain spring lengthens it 2 inches, what weight would lengthen it $\frac{1}{4}$ of an inch? How much would $\frac{3}{8}$ of a pound lengthen it?

2. If a force of 5 pounds is required to move the middle point of a beam $\frac{1}{8}$ of an inch, what force would move it $\frac{1}{4}$ of an inch?

3. A 2-pound force is applied to the rim of a wheel 9 inches in diameter in the torsion apparatus described in section 125, and the end of the rod twists through 3°. What force would have to be applied to the rim of a wheel 12 inches in diameter to make the end of the same rod twist through 5°?

4. An experiment to find the relation of the bending of a beam to the load gave the following data:

LOADS in pounds	10	20	30	40	50	60	70
BENDING in inches	0.05	0.10	0.15	0.21	0.25	0.29	0.35

Plot these values, making the loads vertical and the bendings horizontal. What law is here illustrated?

5. A piece of steel piano wire 90 inches long and 0.035 inches in diameter was stretched with various loads as follows:

LOADS in pounds	5	10	15	20	25
STRETCHING in inches	0.016	0.033	0.048	0.064	0.079

Plot a curve to show the relation of the stretching to the load. Make the loads ordinates (vertical) and the stretches abscissas (horizontal).

126. Elastic limit and breaking strength. In the tension experiment in the last section we found that when a sufficiently great load was hung from the wire, the latter did not come back to its original length when the load was removed. It had acquired a permanent "set." The same thing is true of other kinds of stress, and would be noticed in the other experiments if the stresses were made great enough. The smallest stress of any particular kind that will cause a permanent set in a body is called the **elastic limit** of the body for that particular kind of stress. As long as the load is below the elastic limit, Hooke's law holds; but stresses greater than the elastic limit cause deflections greater than Hooke's law predicts.

If we still further increase the load in the tension experiment, we finally reach a load so great that the wire stretches very rapidly and almost immediately breaks. This is also true of other kinds of tests, such as tests for bending. The smallest stress of any particular kind that will cause a body to give way is called the ultimate or **breaking strength** of the body for that particular kind of stress.

Usually the elastic limit of anything is much smaller than its breaking strength. But certain materials, such as glass, follow Hooke's law up to their breaking points, and never show a permanent set.

127. Commercial testing. Tension, compression, and transverse tests on specimens of steel and other metals are made commercially on a machine like that shown in figure 168.

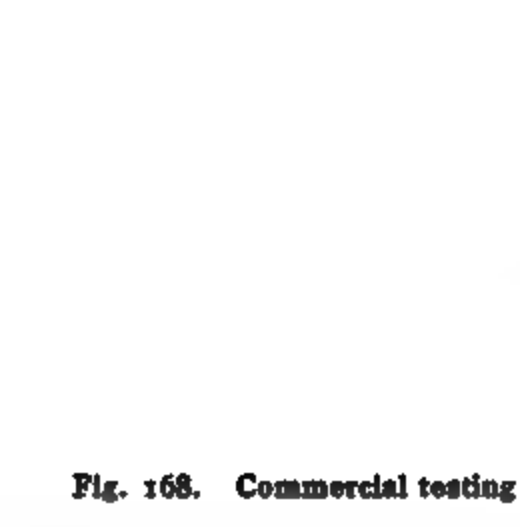

Fig. 168. Commercial testing machine.

The machine consists essentially of three parts: (1) the *platform balance*, which has a weighing table C and three levers so constructed as to act as a single lever; (2) the *stressing mechanism*, which pulls down the movable crosshead B by means of four pulling screws with rotating nuts inside the base plate; and (3) the *driving mechanism*, which turns the rotating nuts at varying speeds by power received from a direct-connected electric motor. For tension tests, the specimen is fastened to the stationary crosshead A and to the movable crosshead B. For compression tests it is placed between the movable crosshead B and the weighing table C. For transverse tests, the specimen is supported on two V-blocks placed on the weighing table C, and the top V-block is secured to the movable crosshead B as in compression tests. In all these tests it is possible to operate the machine automatically.

Most commercial testing machines are so arranged that they can draw automatically a **stress-strain curve** for the material under test. A paper-covered drum is turned by a multiplying mechanism attached to the ends of the specimen in such a way that the rotation of the drum is proportional to the stretch or contraction of the specimen. Meanwhile a pencil is moved up and down along the drum and indicates the force applied at each instant.

Figure 169 is an example of such a diagram. The straight portion *OA* is in accordance with Hooke's law. The elastic limit is where the curve begins to bend. It is not very clearly marked but is near *A*. At *B* occurs what is called the "drop of the beam." The specimen undergoes some curious and rather sudden internal rearrangement of molecules and stretches so fast for an instant that the machine cannot keep up. This accounts for the temporary drop in the force exerted by the machine. Between *C* and *D* the specimen stretches more and more rapidly, and final rupture begins to occur at *D*.

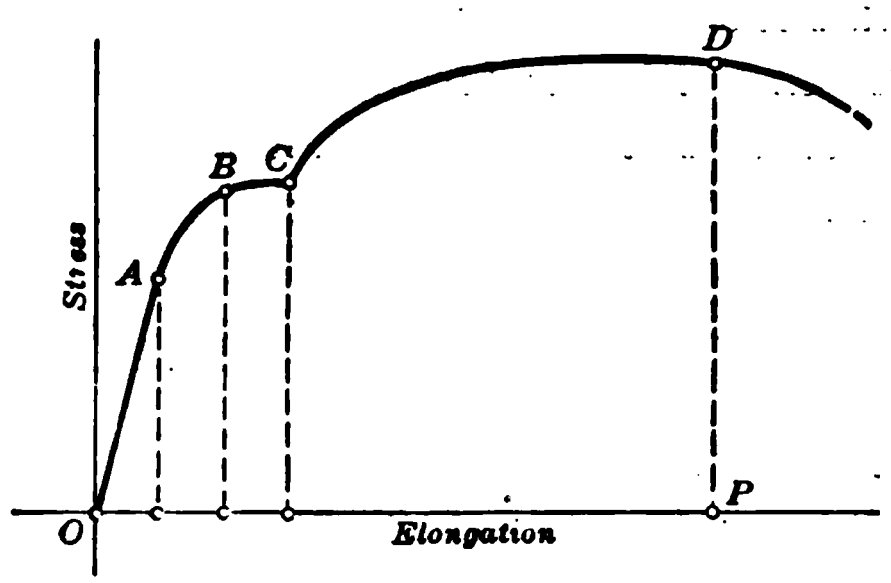

Fig. 169. Stress-strain curve.

The interesting quantities determined by such a test are (1) the stress at *B*, which is commonly used instead of the rather vaguely defined elastic limit *A*, (2) the stress at *D*, which is the ultimate strength of the specimen, and (3) the elongation *OP* at rupture. The latter is a useful indication of toughness or lack of brittleness.

128. Factor of safety. An engineer, when designing a bridge or a machine, must be absolutely sure that no part of it will ever be subjected to a stress greater than its elastic limit; for if this were to happen, that part would be permanently deformed, and this would weaken the rest of the structure, or at least throw it out of alignment. He therefore plans to make each member strong enough to carry several times as much load as will probably ever be imposed on it. This is

partly to provide for any unforeseen temporary overloading of the structure, and partly because there may be, even in materials of the best quality, imperceptible flaws that would make the completed member less strong than it seems to be. *The number of times that the load planned for is greater than the load expected is called the* ***factor of safety.***

The factor that should be used varies with the material; thus it is commonly 10 for brick and stone, and only 4 for steel. It also varies with the nature of the load; thus it is commonly larger when the load is to be intermittent, as in machines or railroad bridges, than when it is to be steady, as in buildings. Often the factor for buildings is taken larger than would otherwise be necessary, so that there may be no danger of deflections in the walls and ceilings great enough to crack the plaster.

SUMMARY OF PRINCIPLES IN CHAPTER VI

Stress refers to force acting.

Strain refers to deformation produced.

Hooke's law: Strain is proportional to stress.

True for all kinds of stress, such as tension, compression, bending, and twisting.

Elastic limit is the minimum stress that will produce a permanent set. Hooke's law applies only for loads below the elastic limit.

Breaking strength is the minimum stress that will cause a body to give way.

$$\text{Factor of safety} = \frac{\text{elastic limit}}{\text{permissible load}}.$$

QUESTIONS

1. Name five practical applications of the elasticity of steel in springs.

2. Arrange an apparatus to determine whether or not Hooke's law applies to a rubber band.

3. Name the kinds of stresses which are acting on the following: wires of a piano, crank shaft in an engine, smokestack, table leg, belt, pump piston, and threads holding buttons on a coat.

4. In the loading of long thin columns, what other effects besides simple compression have to be considered?

5. Where is the elastic medium in the human body which prevents injury to the brain when we jump?

6. Try to find out what is meant by the "fatigue" of metals (see an encyclopedia).

7. What advantages has reënforced concrete over ordinary concrete for building purposes?

8. How are the walls of high office buildings supported, and why?

PRACTICAL EXERCISES

1. Automatic door-closer. Figure 170 shows how one of these devices is attached to a door and how it is built. Get one of these

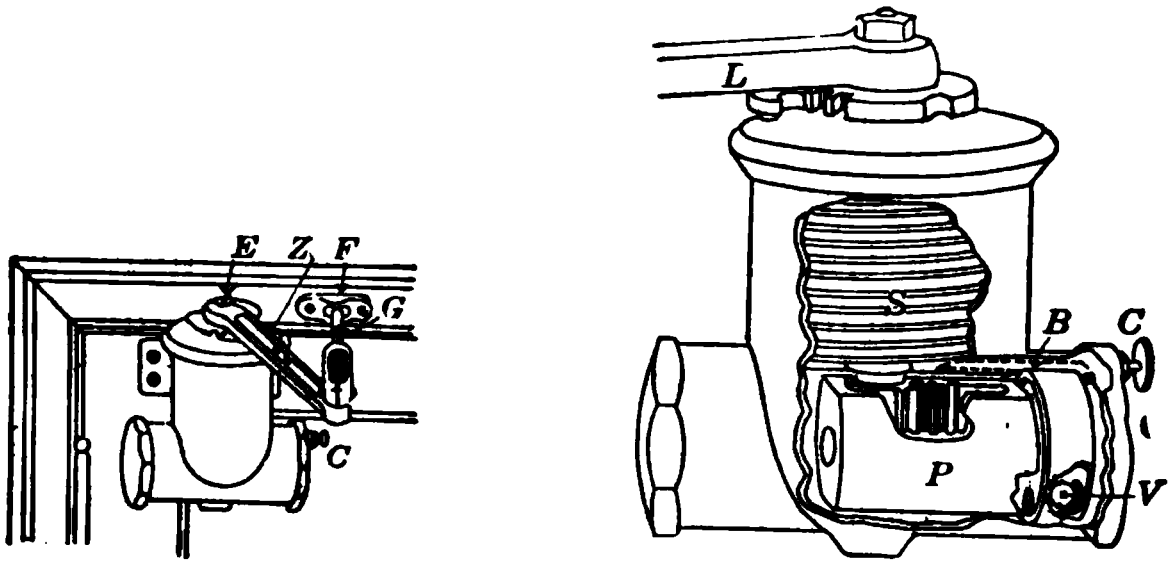

Fig. 170. Automatic door-closing spring.

attachments from a hardware dealer and find out just how it works. How is the banging of the door prevented in this device?

2. Shock absorber. What is the purpose of a shock absorber on an automobile? Find out how some form of absorber works. What principles are applied?

CHAPTER VII

ACCELERATED MOTION

Speed and acceleration — laws of motion at constant acceleration — falling is motion at constant acceleration — value of acceleration of gravity — projectiles.

129. Average speed. If a man walks 12 miles in 3 hours, we say that he averages 4 miles an hour. To be sure, at any particular point on his journey he may have been going faster or slower; but his average speed or velocity is 4 miles an hour. If we know that the average speed of a steamer is 22 miles an hour, we can find a day's run by multiplying the average speed by the number of hours in a day; thus, $22 \times 24 = 528$ miles. In general,

Distance = average speed × time.

Speed is expressed in various ways; for example, we say that an automobile is traveling at the rate of 25 miles an hour, that a steamer is doing 18 knots, or 18 nautical miles an hour, and that a rifle ball goes 2000 feet per second. Engineers and other scientific men commonly express speeds in miles per hour (mi./hr.), feet per second (ft./sec.), or centimeters (or meters) per second (cm./sec. or m./sec.). The following table gives some typical speeds:

TABLE OF SPEEDS

Soldiers marching	3	mi./hr.	=	4.4	ft./sec.	=	1.3	m./sec.
Athlete (mile run)	14	mi./hr.	=	20.5	ft./sec.	=	6.3	m./sec.
Athlete (100 yds.)	20.4	mi./hr.	=	30	ft./sec.	=	9.1	m./sec.
Ocean steamer	27	mi./hr.	=	39.6	ft./sec.	=	12.1	m./sec.
Express train	50	mi./hr.	=	73.5	ft./sec.	=	22.4	m./sec.
Wind in hurricane	110	mi./hr.	=	162	ft./sec.	=	49	m./sec.
Airplane	194	mi./hr.	=	285	ft./sec.	=	87	m./sec.
Sound	750	mi./hr.	=	1100	ft./sec.	=	335	m./sec.
Rifle ball	1360	mi./hr.	=	2000	ft./sec.	=	610	m./sec.

Problems

(In solving these problems use data given in table of speeds when necessary.)

1. Sixty miles an hour equals how many feet per second? (You would do well to remember this number.)

2. If the distance across the Atlantic Ocean is 3000 miles, how many days will it take a steamer to cross?

3. How long will it take an express train to cover 40 miles?

4. In what time (minutes and seconds) can the athlete referred to in the table do the mile run?

5. The time for a 4-mile boat race was 21 minutes and 10 seconds. (*a*) What was the average speed in feet per second? (*b*) In miles per hour?

6. If an automobile wheel is 32 inches in diameter and the car is moving at the rate of 20 miles an hour, how many revolutions per minute (r. p. m.) does the wheel make?

7. An automobile is going 30 miles an hour. A motor cycle is 5 miles behind it and going 40 miles an hour. How long will it take the motor cycle to overtake the automobile?

8. A rifle is fired at a target half a mile away. How long after it is fired does the sound it makes against the target reach the man with the rifle?

130. Variable speed. When a train is starting out from a station, it is gaining speed, and when it is approaching a station where it must stop, it is losing speed. So we see that, on account of stops and differences in grade, the speed of a train is not uniform or constant, but is changing or variable. A loaded sled which starts at the top of a long hill gains in speed as it descends the hill; but when it reaches the level ground at the bottom, it is retarded and loses speed until it stops. Its speed or velocity, starting at zero, has increased to a maximum and then has decreased to zero again. Similarly, the speed of a projectile from a big gun or of the piston of an engine is not uniform but variable.

Formerly, when a policeman wished to determine the speed of an automobile at any point, he measured off some convenient

distance near the point and then got the time which elapsed while the automobile traveled the fixed distance. For example, if the measured distance, sometimes called a "trap," was a quarter of a mile and the time was 20 seconds, the speed was three quarters of a mile per minute, or 45 miles per hour. But if the driver of the automobile was aware of the trap and was driving at a dangerously high speed at the beginning of the trap, he would slow down so that his average speed over the measured distance would be within the limit. To catch such a driver, that is, to get his speed more accurately *at any point*, one took as short a distance as was consistent with an accurate measurement of the time.

131. The speedometer. Nowadays a traffic policeman trails a speeding automobilist on a motor cycle, and determines the speed at any given instant by reading his own speedometer.

The essential parts of a speedometer of the centrifugal type are shown in figure 171. A shaft *AA* runs in ball bearings and is driven through a flexible shaft by a gear attached to one of the wheels, or to the main driving shaft. The faster the car goes, the faster the shaft *AA* rotates. Two or three weights *BB* are carried by links hinged at *C* to the shaft and at *D* to a collar that can slide up and down the shaft. The faster the shaft rotates, the more the weights *BB* tend to fly out. This tendency is balanced by the spring which pushes down on the collar *D*. At any given speed the collar *D* rises just so much against the increasing push of the spring, and moves the pointer *F* by means of the bell crank and geared sector. The light spring *H* serves to keep the little roller pressing against the collar *D*. A speedometer also measures distance by making the revolutions of the shaft *AA* drive a counting device *K* through a double worm-gear speed reduction *MN*.

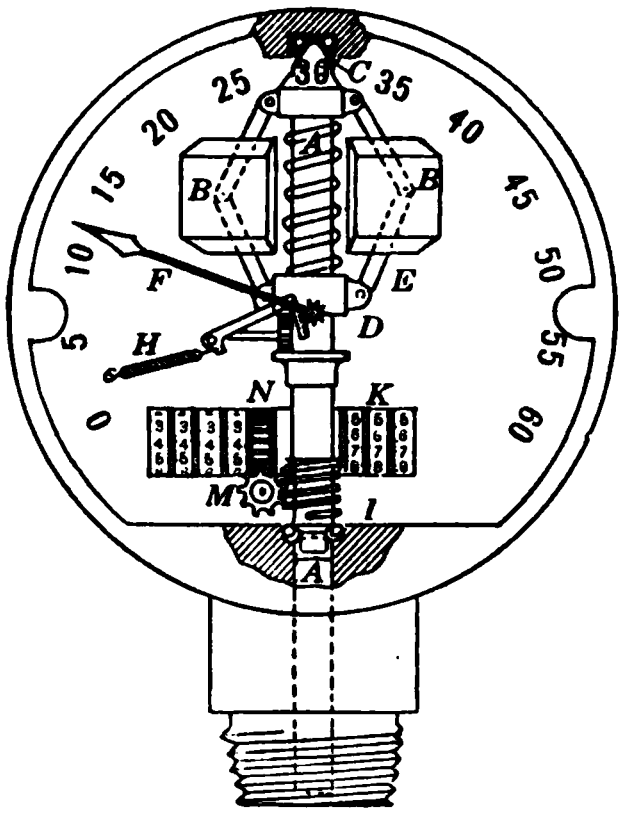

Fig. 171. Diagram of the essential parts of an automobile speedometer.

132. Acceleration. It is unpleasant to be on a street car when it starts or stops too suddenly. This suggests the problem of measuring a ***rate* of change of speed**, which is called **acceleration.** It has been found that a city street car standing at rest can safely gain speed so that at the end of 10 seconds it is going 15 miles per hour. Assuming that this gain in speed is made at a constant rate (only constant accelerations will be discussed in this book), the speed of the car increased 1.5 miles-per-hour every second. In other words, the acceleration was 1.5 miles-per-hour per second. Or, since 15 miles an hour is 22 feet per second, we can say that the gain in speed each second is 2.2 feet per second.

In general,

Acceleration = change in speed per *unit time*,

and acceleration is always to be expressed as so many **speed units per time unit.** Since there are many different speed units, such as miles-per-hour, kilometers-per-hour, feet-per-second, and centimeters-per-second, there are many ways of expressing the same acceleration. Thus the acceleration of the electric car just mentioned is

	Velocity Unit	Time Unit
	1.5 miles-per-hour	per second,
or	2.4 kilometers-per-hour	per second,
or	2.2 feet-per-second	per second,
or	67.0 centimeters-per-second	per second.

All these statements mean exactly the same thing. Engineers sometimes use the first two expressions for acceleration; other scientific men more commonly use the last two. It is convenient to abbreviate "feet-per-second per second" as ft./sec.^{2} and "centimeters-per-second per second" as cm./sec.^{2}; but each of these abbreviated expressions means simply so many velocity units gained per second.

The accelerating rates of cars vary according to service and equipment, but the following rates are common in practical operation:

TABLE OF ACCELERATIONS

Steam locomotive, freight service,	0.1–0.2 miles-per-hr. per sec.
Steam locomotive, passenger service,	0.2–0.5 miles-per-hr. per sec.
Electric locomotive, passenger service,	0.3–0.6 miles-per-hr. per sec.
Electric car, interurban service,	0.8–1.3 miles-per-hr. per sec.
Electric car, city service,	1.5 miles-per-hr. per sec.
Electric car, rapid transit service,	1.5–2.0 miles-per-hr. per sec.

133. Positive and negative acceleration. When the speed is **increasing**, the acceleration is said to be **positive**, and when the speed is **decreasing**, the acceleration is **negative**. Thus, when a baseball is dropped from a tower, it goes faster and faster; it has *positive acceleration*. When, however, it is thrown upward, it goes more and more slowly; it has *negative acceleration*, or *retardation*.

134. Relation of speed to time at constant acceleration. If we know the acceleration of any body, we can easily compute its speed at any time after it started.

FOR EXAMPLE, if the rate of acceleration of a train is 0.2 miles-per-hour per second, how fast is it moving one minute after it starts? One minute equals 60 seconds. If the train gains 0.2 miles-per-hour every second, then its speed, 60 seconds after starting, would be 60 times 0.2, or 12 miles per hour.

LAW I. *If the acceleration is constant, the speed acquired is directly proportional to the time.*

If a body starts from rest, we have

$$\text{Final velocity} = \text{acceleration} \times \text{time}$$

$$v = at. \qquad \text{(I)}$$

PROBLEMS

1. If the speed of an electric car increases every second 2 feet per second, in how many seconds will its velocity be 25 feet per second?

2. A train in leaving a station gains speed at the rate of 0.5 miles-per-hour per second. What will be its speed (miles per hour) at the end of half a minute?

3. Express 1 mile-per-hour per second in feet-per-second per second.

4. A body has a speed of 16 feet per second at a certain instant, and 3 seconds later it has a speed of 112 feet per second. What is its acceleration?

5. A train starting from rest has, after 33 seconds, a speed of 15 miles an hour. What is the average acceleration,

(*a*) In miles-per-hour per second?
(*b*) In feet-per-second per second?

6. If a locomotive can give a train an acceleration of 5 feet-per-second per second, how long will it take, after slowing down for a crossing, to increase the speed of the train from 22 feet per second to 82 feet per second?

7. An automobile was going at the rate of 30 miles an hour. The brakes were applied and it was stopped in 10 seconds. What was the rate of retardation expressed (*a*) in miles-per-hour per second, and (*b*) in feet-per-second per second?

8. The negative acceleration (retardation) in stopping electric trains is seldom greater than 4 feet-per-second per second. How long does it take to stop such a train running 60 miles an hour?

9. What is the acceleration of a train if the initial speed is 45 feet per second, and after 5 seconds the speed is 15 feet per second?

10. What acceleration (feet-per-second per second) is needed in order that an airplane may get up a speed of 60 miles an hour in half a minute?

135. Relation of distance to time at constant acceleration. Suppose a sled gains speed at a constant rate as it goes down a hill. If its acceleration is 3 feet-per-second per second, how far will it go in the first five seconds after starting from rest? We have already seen that its velocity at the end of five seconds will be 5×3, or 15 feet per second. Now, it started from rest, that is, its *initial velocity* was zero, and gradually its speed increased until its *final velocity*, at the end of five seconds, is 15 feet per second. Therefore its *average velocity* is one half the sum of its initial and final velocities, or 7.5 feet per second.

$$\textbf{Average velocity} = \frac{\textbf{initial velocity} + \textbf{final velocity}}{2}.$$

We have already learned (section 129) that the distance traversed is the product of the average velocity and the time.

So in this case the sled has gone 7.5×5, or 37.5 feet.

In general, for a body *starting from rest*, the average velocity is one half the final velocity:

$$\text{Average velocity} = \tfrac{1}{2} v.$$

But we already know that the final velocity is $v = at$; then,

$$\text{Average velocity} = \tfrac{1}{2} at.$$

Therefore the distance is

$$s = \tfrac{1}{2} at \times t$$

$$s = \tfrac{1}{2} at^2. \qquad \textbf{(II)}$$

LAW II. *If the acceleration is constant, the distance traversed from rest varies as the square of the time.*

In using this law, acceleration should be expressed in ft./sec.^{2} or m./sec.^{2} or cm./sec.^{2}, and t in seconds.

136. Relation of speed to distance at constant acceleration. Suppose we wished to know how far the rapid transit electric car mentioned in the table in section 132 would have to run to develop a speed of 30 miles an hour, starting from rest. Since the question is concerned only with speed, distance, and acceleration, it is convenient to have an equation involving only v, s, and a.

From equation (I) we have

$$t = \frac{v}{a}$$

and from equation (II),

$$s = \tfrac{1}{2} at^2 = \tfrac{1}{2} a \times \frac{v^2}{a^2} = \frac{v^2}{2a}.$$

Then, $$v^2 = 2as. \qquad \textbf{(III)}$$

LAW III. *If a body starts from rest and the acceleration is constant, the speed varies as the square root of the distance traversed.*

Equation (III) enables us to answer the question about the electric car.

$$v = 30 \text{ miles per hour} = 44 \text{ feet per second}$$
$$a = 2.2 \text{ feet-per-second per second}$$
$$s = \frac{v^2}{2a} = \frac{44^2}{2 \times 2.2} = 440 \text{ feet.}$$

Notice that 30 miles per hour and 2.2 feet-per-second per second could not be substituted directly, because two different kinds of time units, namely, hours and seconds, and two different kinds of distance units, namely, miles and feet, are involved.

In general, all the quantities substituted in any equation must first be expressed in **consistent units.**

Remember that laws II and III hold *only for bodies starting from rest.* It will save time to *memorize* equations (I), (II), and (III). Notice that there is an equation for each pair of quantities v and t, s and t, and v and s. *Always use the equation that gives what is wanted directly from the data.*

137. Negative acceleration. Suppose that an engineer, running at 50 miles an hour, sees a child on the track 200 yards ahead. If his emergency air brakes can give him a retardation of 4 feet-per-second per second, can he stop in time?

Here we have a problem in retardation, or negative acceleration. Let us think of the problem the other way around. Evidently if the engineer could stop within a given distance at a given retardation, he could get up speed within the same distance with an equally great acceleration. So we may ask instead whether the engineer could get up to a speed of 50 miles an hour within 200 yards, if accelerating at 4 feet-per-second per second. The answers to the two questions are the same.

Since the quantities involved are a velocity v and a distance s, we use equation (III).

$$v = 50 \text{ miles an hour} = 73.3 \text{ ft./sec.}$$
$$a = 4 \text{ ft./sec.}^2$$

Then $$s = \frac{v^2}{2a} = \frac{(73.3)^2}{2 \times 4} = 672 \text{ feet} = 224 \text{ yards.}$$

So the engineer can *not* stop in time.

PROBLEMS

(Assume constant acceleration.)

1. If a locomotive can give its train an acceleration of 0.6 feet-per-second per second, in what distance can it develop a speed of 60 feet per second, starting from rest?

2. A boy runs toward an icy place in the sidewalk at a speed of 20 feet per second and slides on it 16 feet. What is the (negative) acceleration?

3. How far will a marble travel down an inclined plane in 3 seconds if the acceleration is 50 centimeters-per-second per second?

4. A motor cycle starting from rest acquires a velocity of 45 miles an hour in 1.5 minutes. What is the acceleration in miles-per-hour per second?

5. How many yards does the motor cycle go in problem 4?

6. In an advertisement for a certain brake lining it is stated that (*a*) an automobile moving 15 miles an hour can stop in 20.8 feet; and (*b*) if moving 30 miles an hour it can stop in 83.3 feet. Compute the acceleration (ft./sec.^{2}) in each case.

7. If the acceleration of an automobile is 3 feet-per-second per second, what speed will it acquire in going 100 yards, starting from rest?

8. An automobile is moving at the rate of 10 miles an hour, when the driver presses the accelerator, thus giving the car an acceleration of 3 feet-per-second per second. How many miles an hour will the car be moving at the end of 5 seconds?

138. Falling is motion at constant acceleration. It is possible to determine in the laboratory the time it takes a body to fall various distances. The results of an actual series of such experiments are as follows:

DISTANCES	TIMES	RATIO OF TIMES
36 cm.	0.272 sec.	3
64	0.363	4
100	0.452	5
144	0.542	6

It will be seen that these distances vary almost exactly as the squares of the times. Thus, 36 is to 64 as 3^2 is to 4^2. This

we have just seen to be the case when the acceleration is constant (see law II). Therefore *falling is a case of motion at constant acceleration.*

A freely falling body acquires velocity so rapidly that it is difficult to make observations upon it directly. Long ago Galileo hit upon the plan of studying the laws of falling bodies by letting a ball roll down an incline. In this way he "diluted" the force of gravity and increased the time of fall so that it could be measured more accurately.

139. Galileo's experiment on the inclined plane. Galileo cut a trough one inch wide in a board 12 yards long, and rolled a brass ball down the trough. After about one hundred trials made for different inclinations and distances, he concluded that the distance of descent for a given inclination varied very nearly as the square of the time. It is remarkable that he was so successful in this experiment when we consider how he measured the time. He attached a very small spout to the bottom of a water pail and caught in a cup the water that escaped during the time the ball rolled down a given distance. Then the water was weighed and the times of descent were taken as proportional to the ascertained weight.

These experiments of Galileo are especially interesting because they led him to change his theories about the distance and time of falling bodies. He seems to have been one of the first of the early philosophers who thought it necessary to test his theories by experiment.

140. All freely falling bodies have the same acceleration. In 1590, people still believed that heavy objects fell faster than light objects; in other words, that the speed of a falling body depended upon its weight. But Galileo maintained that all bodies, if unimpeded by the air, fell the same distance in the same time, and that the only thing that caused some objects, like pieces of paper or feathers, to fall more slowly than pieces of metal or coins was the resistance of the air. To convince his doubting friends and associates he caused balls of different

sizes and materials to be dropped at the same instant from the top of the leaning tower of Pisa. They saw the balls start together, and fall together, and heard them strike the ground together. Some were convinced, others returned to their rooms to consult the books of the old Greek philosopher, Aristotle, distrusting the evidence of their senses.

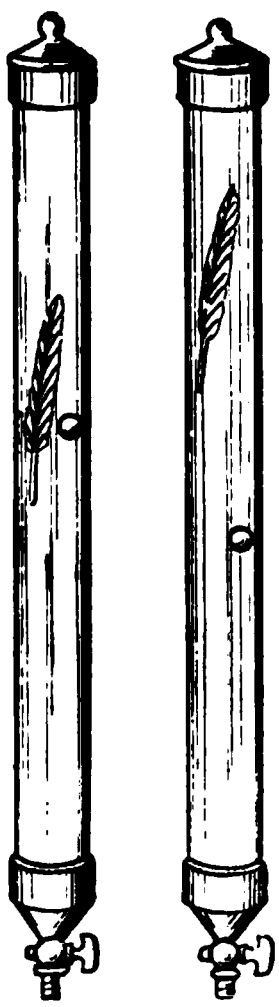

Fig. 172. Feather and coin fall together in a vacuum.

Later, when the vacuum pump was invented, the truth of Galileo's view was confirmed by dropping a feather and a coin in a vacuum tube.

If we place a piece of metal and some light object, like a bit of paper or pith or a feather, in a long tube (Fig. 172) and pump out the air, we find that when we suddenly invert the tube, the two objects fall side by side from the top to the bottom. If we open the stopcock, letting the air in again, and repeat the experiment, we find that the metal falls to the bottom first.

141. Value of acceleration of gravity. It is possible to determine the value of the acceleration of gravity from the experimental data obtained in measuring the time of a free fall (section 138); it is also possible to compute the value of this constant from the data got in the experiment of rolling a ball down an incline. Neither of these methods, however, yields as precise results as are obtained in experiments with **pendulums.**

We are all familiar with the pendulum as a means used to regulate the motion of clocks. It was long ago discovered by Galileo that the successive small vibrations of a pendulum are made in equal times; and that *the time of vibration does not depend on the weight or nature of the bob, or the length of the swing*, but *does vary directly as the square root of the length of the pendulum, and inversely as the acceleration of gravity.* This is expressed in the following formula:

$$t = \pi \sqrt{\frac{l}{g}}$$

where t is the time in seconds of a single vibration, l is the length of the pendulum in centimeters, g is the acceleration of gravity in centimeters-per-second per second, and π is 3.14.

We can measure t and l directly and π is known, so we may compute g from the formula; thus,

$$g = \frac{\pi^2 l}{t^2}.$$

The value of the acceleration of gravity is about 980 centimeters-per-second per second, or about 32 2 feet-per-second per second. It varies a little from place to place.

Problems about falling bodies are just like other problems dealing with constant acceleration. In the equations we usually represent the *acceleration of gravity* by g.

Thus, for bodies falling freely from rest,

$$v = gt,$$
$$s = \tfrac{1}{2} gt^2,$$
$$v^2 = 2gs.$$

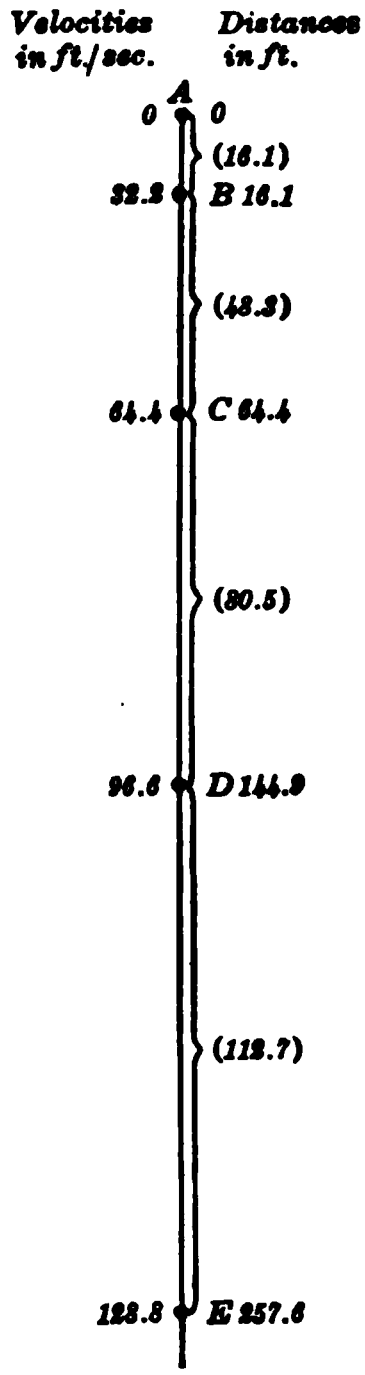

Fig. 173. A freely falling ball.

In figure 173 we have plotted the *distances* in feet covered by a freely falling body in successive seconds and also the *velocities* in feet per second acquired at the end of each second. It will be seen that the distance covered in the first second AB is 16.1 feet, in the second second BC 48.3 feet, in the third second CD 80.5 feet, etc. These successive distances vary as the odd numbers 1, 3, 5, 7, 9, etc.

It will be useful to remember that the speed with which a body must be projected upward to rise to a given height is the same as the velocity which it will acquire in falling from the same height. (Compare this statement with section 137.)

PROBLEMS

(Neglect air resistance and assume $g = 32$ ft./sec.^{2}, or 980 cm./sec.^{2}.)

1. Make a table like the following, running up to $t = 5$ seconds, and fill it in.

NUMBER OF SECONDS, t	TOTAL DISTANCE FALLEN, s (FT.)	SPEED AT END OF EACH SECOND, v (FT./SEC.)	TOTAL DISTANCE FALLEN, s (METERS)	SPEED AT END OF EACH SECOND, v (M./SEC.)
1	16	32	4.9	9.8
2	?	?	?	?

2. A stone is dropped from the top of a cliff and strikes at the base in 5 seconds. (*a*) What velocity did it acquire? (*b*) How high is the cliff?

3. If a falling body has acquired a velocity of 150 feet per second, how long has it been falling? How far?

4. How many centimeters does a stone fall in 0.5 seconds?

5. How many centimeters does a stone fall during the fifth second?

6. A rifle is fired straight up with a muzzle velocity of 2000 feet per second. How long before the bullet comes down again? How high will it go? (Assume that air resistance is negligible, which is far from true.)

7. A baseball is thrown up in the air and reaches the ground after 4 seconds. How high did it rise?

8. The weight of a pile driver drops 5 feet at first and later 15 feet. How much faster is it moving when it strikes in the latter case than in the first case?

9. A body is thrown vertically upward with a velocity of 50 meters per second. With what velocity will it pass a point 100 meters from the ground? (HINT. — How high does the body rise?)

10. A weight is hung from the top of the Washington Monument (555 feet). What is the period of such a pendulum?

11. The length of a pendulum which makes a single swing per second in a certain laboratory is found to be 99.3 centimeters. Compute the value of g (cm./sec.^{2}) for that place.

142. Projectiles. A baseball or golf ball in flight, a bomb dropped from an airplane, a rifle bullet, or the projectile from a great gun on a battleship differs from a freely falling body only because of the initial velocity imparted to it by the projecting mechanism.

If there were no air resistance and if gravity did not act at all, the motion of a projectile would be very simple. It would move straight on in whatever direction it had been started and with an unvarying velocity. If, starting from *A* (Fig. 174), it was at 1 at the end of the first second, then after 2 seconds it would be at 2, after 3 seconds at 3, and so on in the straight line *AB*.

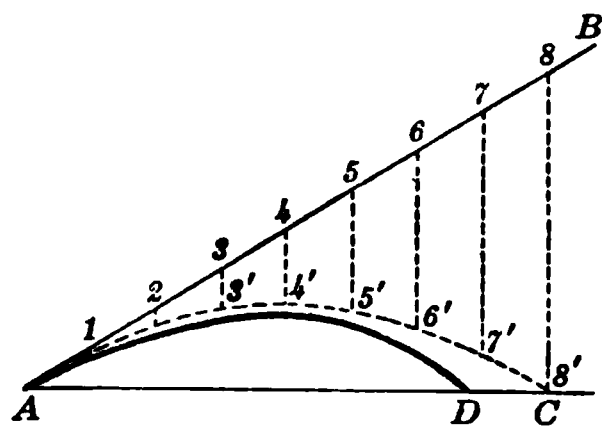

Fig. 174. Path of projectile.

The motion of a real projectile differs from the imaginary motion just described in two respects. In the first place, gravity begins to act on the real projectile the instant it leaves the impelling mechanism, and it begins to fall just as if it were not already in motion. To find where it would be (except for air resistance) at the end of say the third second, we have only to compute how far a body falling freely from rest drops in 3 seconds (namely, 144 feet) and we find the real projectile at 3′, just 144 feet below 3, where it would have been except for gravity. The path *AC* of figure 174 may be called the ideal or vacuum trajectory (path) of the projectile. The real trajectory *AD* is lower, and steeper on the descending side, because of air resistance. This kills out the sidewise motion, so that the projectile takes longer and longer to cover any given horizontal distance and has meanwhile more and more time to fall.

PROBLEMS

(Neglect air resistance.)

1. A rifle is fired horizontally from the top of a cliff which is 144 feet high. The velocity of the projectile is 1200 feet per second. (*a*) How long will it be before it hits the ground? (*b*) How far does it go horizontally?

2. A projectile is fired with a velocity of 144 feet per second and at an angle of 45° to the horizontal. Draw a diagram to show its

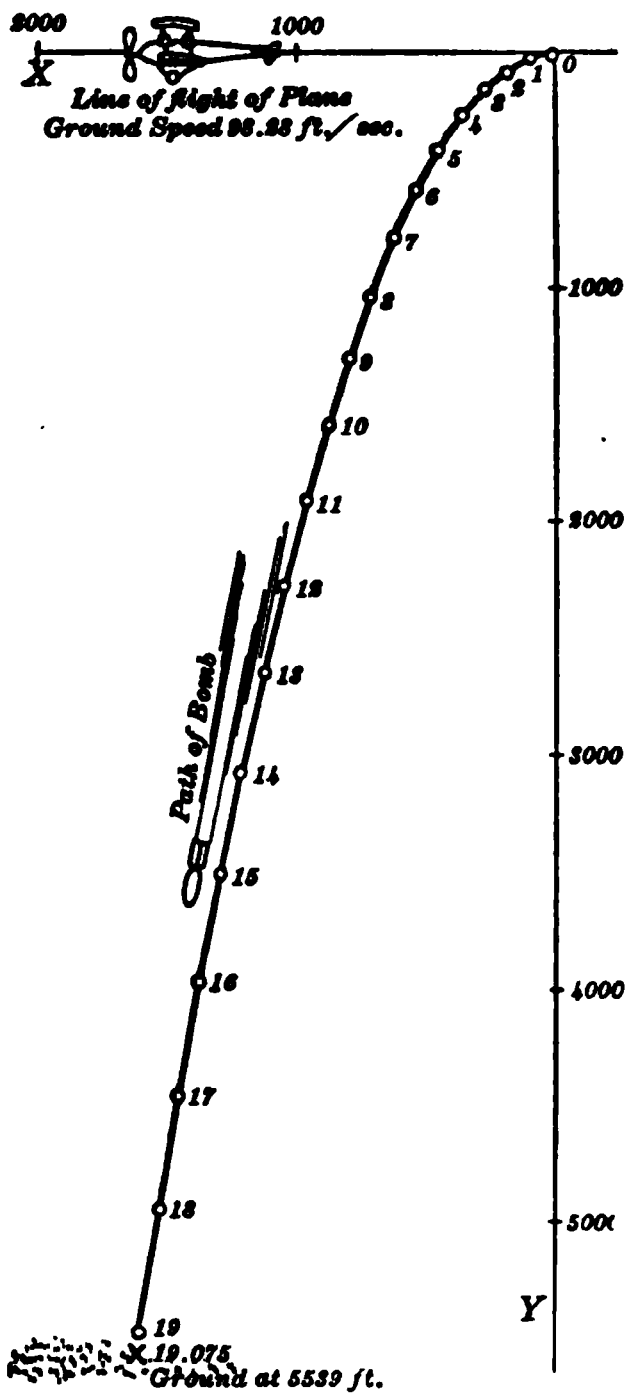

Fig. 175. Actual path of bomb dropped from airplane.

position at the end of each second. (Use a scale $\frac{1}{4}$ inch = 16 feet.) Find (*a*) the greatest height reached and (*b*) the horizontal range.

3. Repeat problem 2, using an angle of elevation of 30° to the horizontal.

4. Figure 175 shows the actual path of a bomb dropped at night from an airplane during a test at Langley Field, Va., during the war. The bomb carried a 2000-candle-power electric light and was photographed each second with two cameras 2630 feet apart. The airplane was flying horizontally at a speed of 98.28 feet per second, and the bomb moved horizontally 1698 feet in the first 18 seconds, and dropped 4965 feet. By how much did the actual path deviate from the theoretical path?

5. The bomb of the last problem moved horizontally 875 feet in the first 9 seconds, and dropped 1287 feet. Are these distances greater or less than would be expected *in comparison with* the figures for 18 seconds? Why?

SUMMARY OF PRINCIPLES IN CHAPTER VII

Average speed $= \dfrac{\text{distance}}{\text{time}}$.

Acceleration $= \dfrac{\text{change in speed}}{\text{time}}$.

Laws of motion at constant acceleration starting from rest:

I. $v = at$. II. $s = \dfrac{at^2}{2}$. III. $v^2 = 2as$.

Value of acceleration of gravity:

$$g = 32.2 \text{ ft./sec.}^2 = 980 \text{ cm./sec.}^2.$$

Projectile combines free fall with straight line motion.

QUESTIONS

1. By means of the apparatus shown in figure 176, one ball is dropped and at the same instant another is thrown horizontally. Which strikes the floor first?

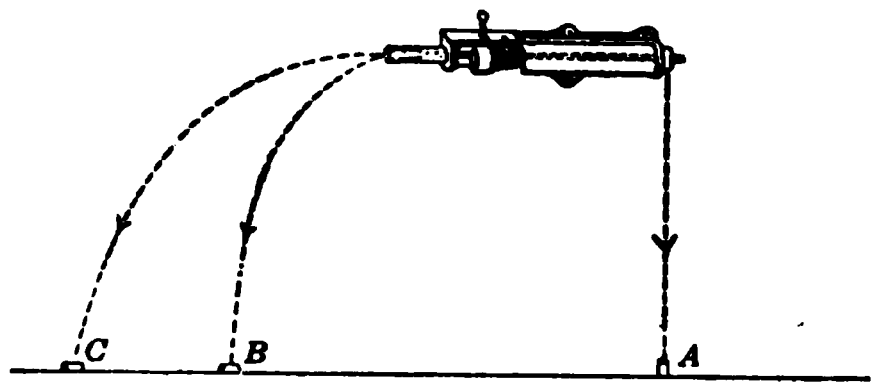

Fig. 176. Apparatus for dropping a ball and throwing another ball at the same instant.

2. Find out what Galileo observed in connection with the chandelier in the cathedral at Pisa.

3. How must the pendulum bob be moved on a clock which is running too fast?

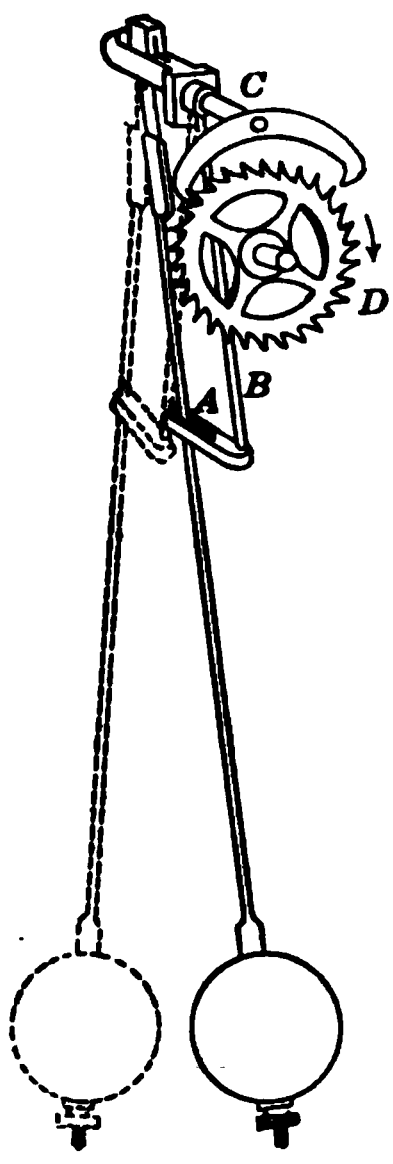

Fig. 177. Escapement wheel and pendulum of a clock.

4. What is the difference between a simple pendulum and a compound pendulum? What is meant by the center of oscillation? What is the center of percussion of a baseball bat?

5. Many faucets discharge round, smooth, quiet streams of water. Explain why the diameter of such a stream is smaller at the bottom than near the faucet.

6. What other factors besides air resistance make the real trajectory of a projectile deviate from the ideal trajectory?

PRACTICAL EXERCISES

1. **Acceleration of an automobile.** By means of a stop watch and a speedometer measure the positive and negative acceleration of an automobile under varying conditions. If possible, try the same experiment with an entirely different type of automobile. Discuss your results.

2. **Use of pendulums in clocks.** Examine a dissected Swiss or other pendulum clock, comparing what you find with figure 177. How does the pendulum control the movement of the escapement wheel? What drives this wheel? Examine if you can, and report on the mechanism of a clock in some tower or church steeple.

CHAPTER VIII

THREE LAWS OF MOTION

Newton's laws — inertia — the fundamental proportion of force and acceleration — action and reaction — mass.

143. Newton's laws of motion. We have been *describing* different motions, such as motion at constant speed and motion at constant acceleration. Now we shall try to *explain* different motions by studying the forces that cause them. Practically all that we know about this part of physics dates back to Sir Isaac Newton (Fig. 178), who in 1687 wrote a treatise on the principles (*Principia*) of natural philosophy, or physics. His whole book, and indeed all mechanics since his day, is based on three very simple laws, called **Newton's laws**. The first of them is the law of **inertia**, the second the law of **acceleration**, and the third the law of **interaction**. These will be discussed in turn.

Fig. 178. Sir Isaac Newton (1642-1727). An Englishman, who founded the science of mechanics, and made many important discoveries in light.

144. First law — Inertia. It is a familiar fact that nothing in nature will either start or stop moving of itself. Some force from outside is always required. For example, a horse when starting a wagon, even on an excellent road, has to pull very hard at first; after the wagon is going, the horse can keep

it moving with very little effort; but if he tries to stop it to avoid running over some one, he has to push back hard. So also when a moving ship collides with another ship or a dock, it requires an enormous retarding force to stop her. *This property*, which all matter possesses, *of resisting any attempt to start it if at rest, to stop it if in motion, or in any way to change either the direction or amount of its motion, is called* ***inertia***.

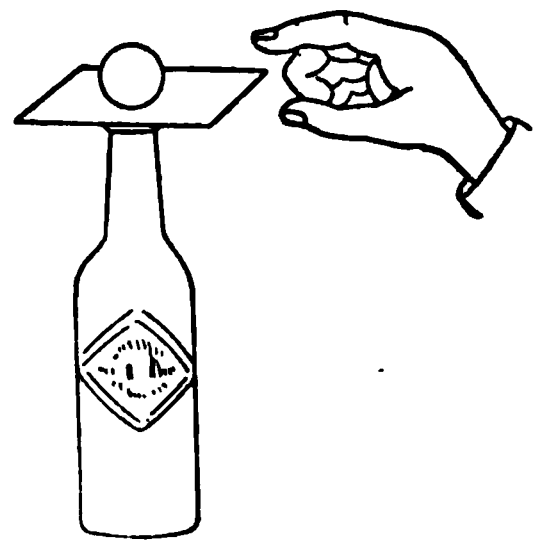

Fig. 179. Inertia keeps the ball from moving.

We may illustrate this property of inertia by balancing a card on a finger with a coin on top and snapping the card out, leaving the coin on the finger. The coin moves only a little because the force, due to friction, is too small to get it started. This may also be done with the apparatus shown in figure 179.

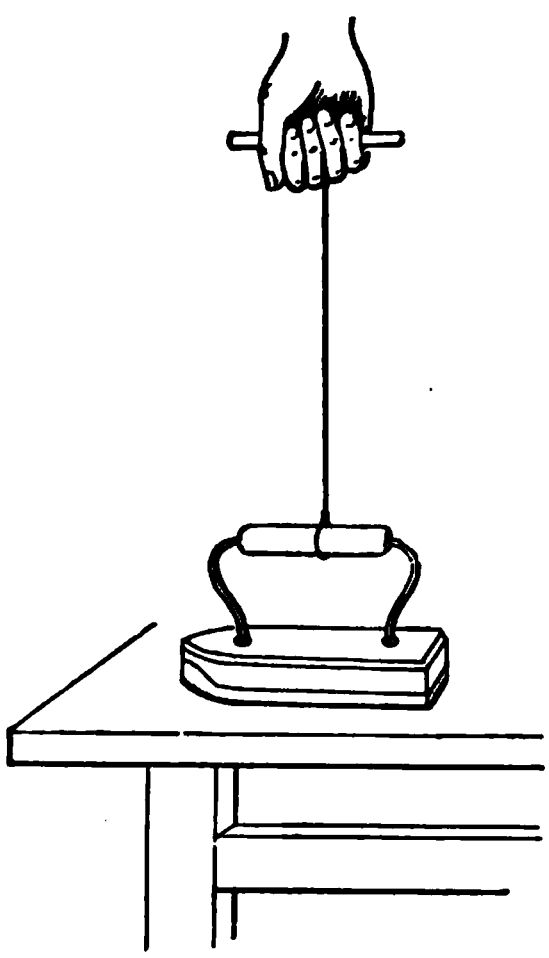

Fig. 180. Inertia holds the flatiron still.

Another interesting experiment is to try to pick up a flatiron by means of a linen thread tied to it (Fig. 180). If we pull slowly, we may be able to do it, but if we pull with a jerk, the thread always breaks, because so much extra force is required to set the flatiron in motion quickly.

This familiar fact, that bodies act as if disinclined to change their state whether of rest or of motion, was expressed by Newton in the following way:

LAW I. *Every body persists in a state of rest, or of uniform motion in a straight line, unless compelled by external force to change that state.*

QUESTIONS

1. If you roll a ball along the ground, why does it not keep going indefinitely?

2. Explain how an automobile provided with a self-starter conforms to Newton's first law.

3. One often sees in a street car the sign, "Wait till the car stops." What has this to do with inertia?

4. If a moving train is suddenly stopped by the emergency brakes, in which direction are the passengers thrown? Explain.

5. A baseball is thrown vertically up into the air. Why does it not keep on moving in a straight line forever?

145. Applications of inertia. A nail can easily be driven into a heavy piece of wood, even when the wood does not lie on a firm foundation, because the quick blow of a hammer does not set the heavy piece of wood in motion to any great extent. It is very difficult, however, to drive a nail through a light stick unless the stick is placed upon a solid foundation, or unless the stick is steadied by the inertia of a heavy sledge hammer, as shown in figure 181.

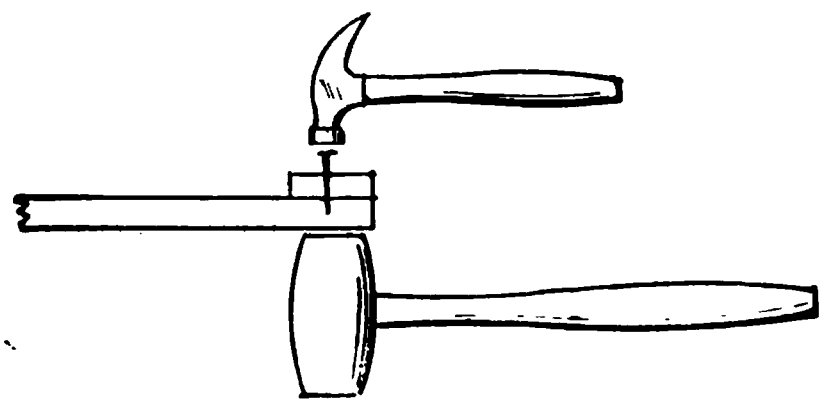

Fig. 181. Inertia of sledge hammer.

When the head of a hammer comes off, the best way to drive it on again is to hit the other end of the handle, rather than the head, against some solid foundation or with another hammer. Why?

146. The centrifugal tendency. The tendency of a body to continue to move in a straight line is very evident when it is desirable to make the body move in a circle. In such a case, a force is required to pull the body in toward the center of the circle, so that it will not fly off on a tangent. Such a force is called a **centripetal force**, meaning a force directed toward the center.

Thus, when an automobile takes a corner at any considerable speed, the passengers find themselves crowded up against the outside cushions, which, by pushing *inward* against them, force them to take the desired curved path through space. The automobile itself has to be pushed *inward* by the friction of the road against its tires if it is to take the curve safely. If the road is so slippery that it cannot exert the necessary *inward* force, the automobile **skids**, that is, starts to fly off on a tangent to the desired course.

When an athlete swings a 16-pound hammer around his head before throwing it, he has to pull it inward because of its inertia. When he stops pulling inward, it flies off on a tangent. So all he has to do to throw it is to let go.

Grinding wheels revolve very rapidly. Sometimes one bursts because the cohesion between its parts is not enough to supply the centripetal force necessary to keep these various parts moving in their respective circles.

The mud on a bicycle wheel stays on the wheel only if the adhesion between it and the tire is great enough to pull it around with the tire; otherwise it flies off on a tangent (Fig. 182).

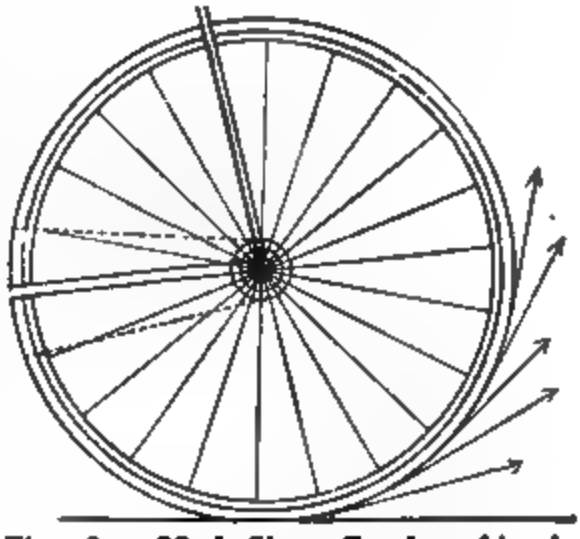

Fig. 182. Mud flies off of a bicycle wheel on a tangent.

In a cream separator (Fig. 183) the denser part of the milk gets outside and crowds the lighter cream inward. This is because the

Fig. 183. A cream separator and diagram of the rotating disks.

greater inertia of the milk (that is, its greater tendency to move along a tangent) prevails over that of the cream. The conical-shaped disks rotate very rapidly and so whirl the milk at a high speed.

All these cases show the **centrifugal tendency**, that is, *the tendency to fly out from the center along a tangent*, which everything manifests when made to follow a curved path.

Machines which make use of the centrifugal tendency to separate one kind of thing from another are often called **centrifuges**. Thus the mother liquor is driven away from the crystallized sugar in refineries (Fig. 184), and the water is driven out of clothes in laundries, in rapidly rotating perforated baskets.

147. Second law — Acceleration. We have been discussing what happens to a body when forces *do not* act on it. Let us now consider what happens when forces *do* act on it.

Whenever an "unbalanced" force is acting on a body, the body has an acceleration in the direction in which the force acts, and the acceleration is proportional to the force. An **unbalanced force** means more push or pull in one direction than in the other.

Fig. 184. Sugar centrifuge used to separate sirup from sugar crystals.

Thus, suppose a locomotive is pulling a train at a constant speed of 50 miles an hour. The engine is certainly exerting a force on the train; but there are other forces, due to friction and air resistance, acting in the opposite direction, and these just balance the pull of the engine. The *net* force forward is zero; if it were not zero, the train would not only be *going* forward but *accelerating* forward; it would be *gaining speed*. It is important to keep in mind that it is *net force* and *acceleration* which always go together, and not net force and motion.

LAW II. *The acceleration of a given body is proportional to the force causing it.*

That is, if any given body is acted on at one time by a force F_1, and at another time by another force F_2, then

$$\frac{F_1}{F_2} = \frac{a_1}{a_2}$$

where a_1 and a_2 are the accelerations produced by F_1 and F_2.

Thus, if we push an automobile with a certain force, and at another time push it twice as hard, it will have twice as much acceleration the second time as the first.

One way to cause a force to act on a body is to let the body fall. In this case the force acting is known, for it is the weight W of the body. The acceleration is also known, for it is g, which is 32.2 feet-per-second per second, or 980 centimeters-per-second per second. So the weight of the body and its acceleration when falling can always be used as two of the numbers in the proportion just mentioned.

That is,
$$\frac{F}{W} = \frac{a}{g}.$$

This enables us to compute the force needed to give a certain body any desired acceleration.

FOR EXAMPLE, a freight train weighs 1000 tons. How great a force is necessary to give it an acceleration of half a foot-per-second per second?

$$\frac{F}{1000} = \frac{0.5}{32.2}$$
$$F = \frac{1000 \times 0.5}{32.2} = 15.6 \text{ tons.}$$

148. Consistent Units. In the equation $F/W = a/g$, it makes no difference in what unit F and W are expressed, *provided only that both are expressed in the same unit.* Both can be expressed in pounds, or in ounces, or in tons, or in kilograms, or in grams, or in a less familiar unit called a "dyne." The **dyne** is a very small unit of force sometimes used in scientific work. It can be defined as 1/980 of a gram weight.* It is about the weight of a milligram. If a force is given in terms of any one of these units, it can be expressed in terms of any other of them with the help of the following table:

1 gram = 980 dynes.	1 dyne = 0.00102 grams.
1 pound = 454 grams.	1 gram = 0.00220 pounds.
1 pound = 445,000 dynes.	1 dyne = 0.00000225 pounds.

* See also problems *4* and *5*, page 180.

Similarly, a and g may be expressed in any unit, *provided only that both are expressed in the same unit.* If both are to be in feet-per-second per second, the numerical value of g is 32.2; if both are to be in centimeters-per-second per second, the numerical value of g is 980.

Problems

(In these problems use 32 ft./sec^2. or 980 cm./sec^2. for g.)

1. What acceleration will a force of 5 pounds produce in a body weighing 16 pounds?

2. What acceleration will a force of 1 gram produce in a body weighing 490 grams?

3. What acceleration will a force of 1 pound produce in a body weighing 1 pound?

4. What acceleration will a force of 1 dyne produce in a body weighing 1 gram? (Note. — The answer to this problem is often regarded as the definition of a dyne.)

5. State accurately in words the definition of a dyne that is referred to in the last problem.

6. A body weighing 10 pounds is observed to have an acceleration of 2 feet-per-second per second. What force is acting?

7. A force of 1 kilogram is observed to produce an acceleration of 9.8 meters-per-second per second in a certain body. How much does the body weigh?

8. A force of 1000 dynes is observed to produce an acceleration of 9.8 centimeters-per-second per second in a certain body. How many grams does the body weigh?

9. An automobile weighing 2 tons is started from rest with an acceleration of 4 feet-per-second per second. How hard is the road pushing forward on the bottoms of the rear tires?

10. A train starting from rest with a constant acceleration takes 44 seconds to get up to a speed of 30 miles an hour. If the train consists of 10 all-steel cars, each weighing 64 tons, what pull is exerted by the engine? (Hint. — Compute acceleration and then find force.)

149. Third law — Interaction. Newton's third law is based on two familiar facts. One way of stating the first of these facts is that there can never be a force acting in nature unless

two bodies are involved, one exerting it and one on which it is exerted. Thus, when a railroad train is pulled, there is an engine that does the pulling; and on the other hand, the engine cannot exert a pull or a push unless there is something to be pulled or pushed. An electric car or an automobile seems, perhaps, to push itself along, but really the track or the road under the wheels is exerting a force on the wheels and pushing the car forward. We have all seen what happens when the car track is so icy or the road so muddy that it cannot push on the wheels. The motor is going just as hard as ever, but the car does not move. Another case is that of any heavy object: there is a force called its weight (force of gravity) pulling it down; but we know that it is the earth that exerts this force.

This, then, is the *first* fact: *whenever there is a force in nature there must be two bodies*, one to exert it and one to receive it.

But we can go further than this. We can say that whenever there is a force in nature there must be not only two bodies involved, but *another force*. That is, forces never exist singly, but always in pairs. If the first force is exerted by a locomotive on a train, the second will be exerted by the train on the locomotive. The train will pull back on the locomotive just as hard as the locomotive pulls forward on the train. If a road is pushing forward on the wheels of the automobile, the wheels must be pushing back on the road.

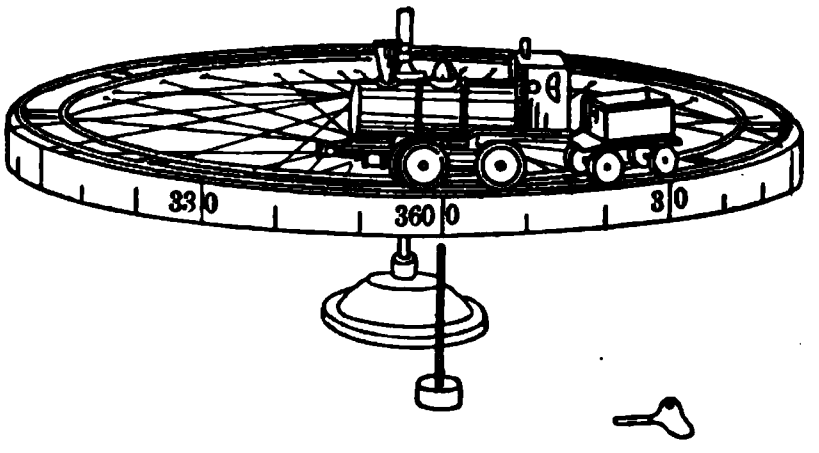

Fig. 185. Track pushes the engine forward.

In order to make this idea seem more real to us, let us try the experiment on a small scale, as shown in figure 185. If we wind up the little toy engine and place it on the circular track, which is so mounted as to turn easily, we find that the track turns around and the rails under the wheels go backwards. If we hold the track fast, the engine goes ahead faster than at first; and if we hold the engine fast, the track turns around backwards faster than at first.

Finally, when any heavy object is pulled downward by the earth, the heavy object must be pulling the earth up with an equal force. This does not seem very likely at first, but that is simply because the force is usually so small and the earth so large that the force has an imperceptible effect on the earth. In the case of a heavy body as large as the moon, the effect is, however, quite perceptible to astronomers. The earth and the moon are actually rotating about a point O (Fig. 186), which is not exactly at the center of the earth. So the moon must continually pull the earth to make its center of gravity move in its circle.

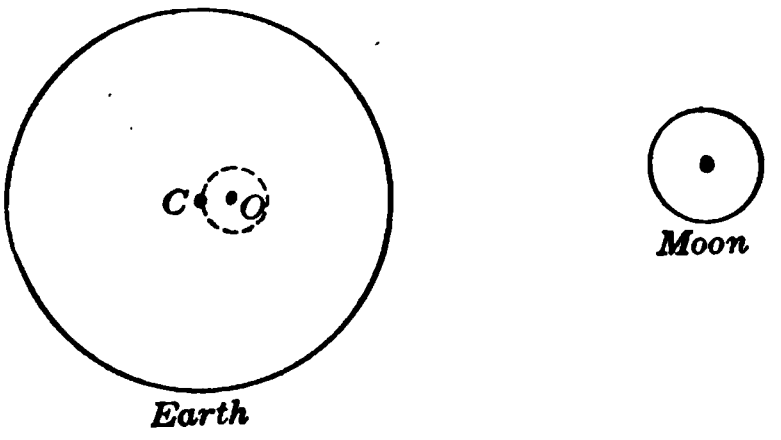

Fig. 186. Rotation of the moon about the earth.

This fact that forces always occur in pairs, one force of each pair being equal and opposite to the other, was expressed by Newton in the following form:

LAW III. *With every action (or force) there is an equal and opposite reaction.*

150. Universal gravitation. The fact that the earth and the moon attract each other is only one example of a very general law, also discovered by Newton, called the **law of universal gravitation.** According to this law every material thing in the universe attracts, and is attracted by, every other material thing. When we lay two bricks near each other on a table, each pulls the other, but the force is so tiny that nobody notices it. Yet the attraction of the sun for the earth, and also that of the earth for the sun, which are forces of exactly the same kind, amount to over 10^{24} (that is, 1 followed by 24 zeros) tons, because the sun and the earth both contain so much matter.

In general, the **attraction** between any two bodies *is pro-*

portional to the amount of matter in each of them, and inversely proportional to the square of the distance between them; that is, the attraction is reduced to a quarter when the distance is doubled, and to one ninth when the distance is trebled.

151. Mass *vs.* weight. "Mass" and "weight" are constantly confused in ordinary conversation. While we have preferred not to use the term "mass" in studying Newton's second law, yet it is well to know its precise meaning so that one can read intelligently the books which make use of it.

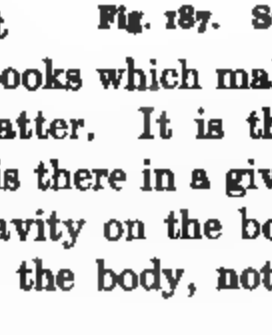

Fig. 187. Standard kilogram.

Mass means quantity of matter. It is the answer to the question, "How much matter is there in a given body?"

Weight means the pull of gravity on the body. The weight of a body is a *force* acting on the body, not a description of what it contains.

The unit of mass is the quantity of matter contained in a certain piece of platinum (the standard kilogram, Fig. 187).

The unit of weight is the pull of the earth on that same piece of platinum, when it is near sea-level and at latitude 45°.

Since a kilogram mass weighs a kilogram under these standard conditions, the mass and the "standard weight" of a body are numerically equal. But if we carry a kilogram mass to the top of a high mountain, and weigh it on a very sensitive *spring* balance, it will weigh less than a kilogram, because it is farther from the center of the earth, and so the earth pulls less hard on it. The reading of the spring balance might be called its "local weight."

Since *all* bodies on the mountain top would weigh less in the same proportion, we can get the *standard weight* of anything

without descending the mountain by weighing it on an *equal-arm* balance against a set of "standard weights." This is what we always do in the laboratory and in the outside world when we want to know weights accurately. So, when we speak of the weight of a body, we almost always mean its "standard weight."

Since $F = \frac{W}{g}a$, and since the standard weight W and the mass M are numerically equal, we shall get the *same value* for F if we write (when using grams, centimeters, and seconds)

$$F = \frac{Ma}{980}$$

or

$$980\,F = Ma.$$

Here F is in *grams;* if we choose, however, to express the force as F' dynes, instead of as F grams, then F and F' will be different numbers, and

$$F' = 980\,F$$

so F' (dynes) $= M$ (grams) $\times\ a$ (cm./sec.^{2}).

This is another way of expressing Newton's second law.

SUMMARY OF PRINCIPLES IN CHAPTER VIII

Newton's laws of motion and the fundamental proportion:

I. Every body continues in a state of rest or of uniform motion in a straight line, unless compelled by external forces to change that state.

II. The acceleration of a given body is proportional to the force causing it. $\frac{F}{W} = \frac{a}{g}$.

III. With every action (or force) there is an equal and opposite reaction.

Mass means quantity of matter in a given body.

Weight means the pull of gravity on the body.

QUESTIONS

1. Why does a train continue to move after the steam is shut off?

2. What does an aviator have to do to round a corner safely, and why?

3. Why can small grinding wheels be safely driven at a greater speed, that is, at more revolutions per minute, than larger ones?

4. Why does a wheel, or any revolving part of a machine, sometimes shake or hammer in its bearings?

5. Explain how a locomotive engineer can tell, when he starts up his train, if one of the cars has been uncoupled from the train.

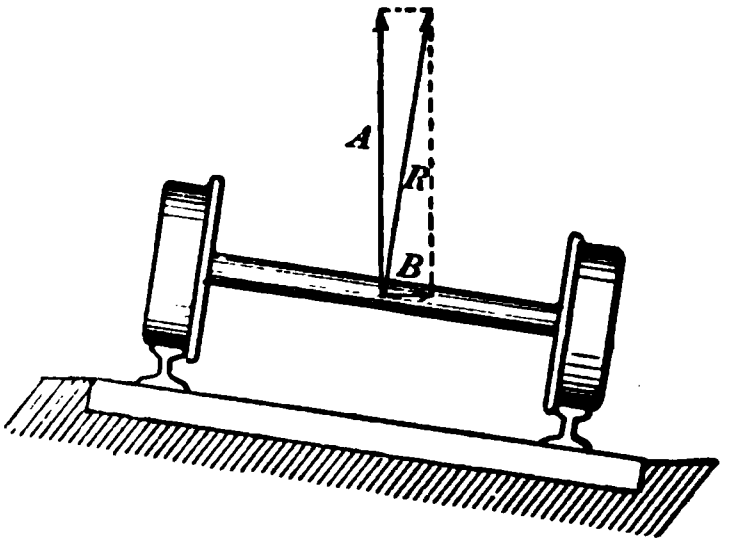

Fig. 188. Banking rails on a curve.

6. Why is an indoor running track "banked" at the turns? Why is a railroad track banked on the curves? Study figure 188, where *A* is the upward push on the wheels, *B* is the centripetal force exerted inward by the rails, and *R* is the resultant.

7. Are the automobile trunk line roads banked on the curves in your state?

8. Explain the working principle involved in a centrifugal pump. See figures 119 and 120.

PRACTICAL EXERCISE

Looping the loop. Construct a working model to illustrate the circus performance called "looping the loop." State the principles involved.

CHAPTER IX

POTENTIAL AND KINETIC ENERGY

Energy — potential energy — how computed — kinetic energy — how computed — transformation of energy — law of conservation of energy.

152. Energy. When a pile is to be driven into the ground, a heavy weight is lifted and allowed to drop on the end of the pile (Fig. 189). Work is done in lifting the heavy weight, and as a result it can do work, namely, drive the pile into the ground. This capacity of the weight in its elevated position to do work we call **energy.**

If we use a heavier weight or lift it to a greater height, we do more work upon it, and as a result the weight has more energy and will drive the pile farther into the ground.

The water rushing out of the nozzle of a Pelton water wheel (section 79) has a great capacity for doing work on account of its rapid motion, and thus has energy. The greater the quantity of water and the more rapid its flow, the larger is the amount of energy available.

Fig. 189. Pile driver hammering a log into the ground.

In general, **the energy of anything may be defined as its capacity for doing work.**

153. Potential energy. The water above the falls at Niagara has great capacity for doing work, by acting on suitable turbine wheels, because of its vast quantity and its elevated position. When a clock or watch spring is wound up, it can drive the clock as it uncoils because of the elastic strain within

it due to its change in shape. The energy that a body has on account of its position or state of strain is called **potential energy.** Thus the energy of the hammer of the pile driver when raised is potential. The energy of the hot compressed gases in the cylinder of a gas engine, just after the explosion, is potential energy.

154. How to compute potential energy. In the case of the pile driver, the potential energy of the hammer depends on its weight and on the height to which it is raised. In other words, the potential energy of the hammer is found by comput ng the work that has been done to place it in its elevated position. In symbols,

$$P.E. = W \times h$$

where W is the weight of the body and h is the vertical distance through which it has been raised. Potential energy (P. E.) is expressed in the same units as work.

For example, suppose the hammer of a pile driver weighs 3000 pounds and is lifted 12 feet; then the potential energy is 3000×12, or 36,000 foot pounds, or 18 foot tons.

155. Kinetic energy. As the hammer of a pile driver is allowed to drop, it gradually loses its potential energy, but gains more and more of another kind of energy as its speed increases. Finally, just as it hits the pile, the potential energy has all been converted into energy of motion, which is called **kinetic energy.**

A heavy flywheel (Fig. 190) will keep machinery running for some time after the power has been shut off, and therefore, *because of its motion,* it can do

Fig. 190. Flywheels on a gas engine when in motion have kinetic energy.

work. The engine had to do work on the flywheel to get it up to speed, and the flywheel, as long as it is moving, can do work on the shaft. The faster and heavier the flywheel, the more work it can do before it comes to rest.

Every body in motion has ***kinetic energy;*** that is, it will do a certain amount of work against a resisting force before it stops moving.

156. How to compute kinetic energy. To compute how much work a moving body can do against a retarding force before it comes to rest, we reverse the problem and compute how much work must be done to start the body and get it up to the given speed.

The fundamental equation for the work done by any force F acting through a distance s is

$$Work = Fs.$$

But we have already (section 147) seen that the force F necessary to get a body whose weight is W started with a given acceleration a may be expressed by the equation,

$$F = \frac{W}{g} a.$$

Therefore, the work done is

$$Fs = \frac{W}{g} as.$$

But the product as can be expressed in terms of the speed v by means of the third law of accelerated motion (section 136).

Thus, $$v^2 = 2\,as, \text{ or } as = \frac{v^2}{2}.$$

So the work done is

$$Fs = \frac{Wv^2}{2g}.$$

Therefore, $$\textit{Kinetic Energy} = \frac{Wv^2}{2g}.$$

In using this equation we must be **consistent** in our **units.** For example, F and W are both forces and must both be expressed in the same unit. Likewise, s, v, and g must all involve the same unit of length. In expressing the velocity v, and the acceleration g, it is customary to use the *second* as the unit of time.

There are several units of work in common use, such as the

foot pound (ft. lb.),
foot ton (ft. T.),
gram centimeter (g. cm.),
kilogram meter (kg. m.), and
dyne-centimeter (" erg ").*

Since each of these work units is a force unit times a distance unit, we can always tell what the unit of kinetic energy is if we notice what force unit and what distance unit were used in expressing W, v and g.

157. Applications of the kinetic energy equation. This equation will help us to solve many useful problems about moving things which involve the idea of **distance.**

FOR EXAMPLE, suppose a 2500-pound automobile running 30 miles an hour is stopped in 90 feet. What braking force is applied?

The speed 30 miles an hour = 44 ft./sec.

Then, substituting in the kinetic energy equation,

$$F \times 90 = \frac{2500 \times (44)^2}{2 \times 32.2}$$

and $$F = 835 \text{ lbs.}$$

Again, suppose the hammer of a pile driver weighs 1500 pounds. It falls 20 feet upon the head of a pile and drives it 18 inches into the ground. What is the kinetic energy of the blow delivered to the pile? What is the average resistance offered by the ground?

The velocity of the hammer when it hits the pile is computed from

$$v^2 = 2gs = 2 \times 32.2 \times 20.$$

Therefore, $$\text{K. E.} = \frac{1500 \times 2 \times 32.2 \times 20}{2 \times 32.2}$$

$$= 30{,}000 \text{ ft. lbs.}$$

Note that the *kinetic energy* of the moving hammer when it hits the pile *is equal to the potential energy* of the uplifted hammer.

If the average resistance is called F, we have

$$F \times 1.5 = 30{,}000 \text{ ft. lbs.}$$

$$F = 20{,}000 \text{ lbs.}$$

158. Kinetic energy different from momentum. There is another property of moving bodies which is often confused with kinetic energy. It is called **momentum.** Its value is $\frac{Wv}{g}$, while kinetic energy is $\frac{Wv^2}{2g}$.

* The dyne-centimeter is usually called an **erg**; since it is a very small unit of work, the **joule** = 10^7 ergs is often used instead.

The amount of momentum that an accelerating body gains per second is a measure of the net force acting. To prove this, we notice that if the body starts from rest, the gain in momentum per second is $\frac{Wv}{gt}$. But $\frac{v}{t}$ is the acceleration a, and $\frac{Wa}{g}$ is equal to the net force acting (section 147).

Also, the amount of *momentum* a moving body has is an indication of *how long* it will move against a given resistance; just as its *kinetic energy* indicates *how far* it will move before it stops. To prove this, we notice that $Ft = \frac{Wv}{g}$. One should be careful not to say "momentum" when one really means kinetic energy, or "energy" when one means momentum.

PROBLEMS

(State the unit in which each answer is expressed.)

1. What is the kinetic energy of a baseball weighing one third of a pound if its velocity is 64 feet per second?

2. What is the kinetic energy of a 150-ton locomotive going 60 miles an hour?

3. What is the kinetic energy of a 9.8-kilogram weight which has been falling long enough to have a velocity of 12 meters per second?

4. What is the kinetic energy of a 16-gram bullet whose velocity is 600 meters per second?

5. Find the kinetic energy *in ergs* of a stone weighing 20 grams when it is thrown with a velocity of 800 centimeters per second.

6. The 14-inch guns on some of the United States warships fire a projectile weighing 1400 pounds and are said to give it a "muzzle energy" of 65,600 foot tons. What is the velocity of the projectile as it leaves the gun?

7. What resistance is necessary to stop a body whose kinetic energy is 90,000 ergs, in a distance of 3 meters?

8. A boy weighing 100 pounds starts to slide on ice at a speed of 20 feet per second. What is his initial energy? If the retarding force due to friction is 40 pounds, how far will he go before stopping?

9. How great a force in excess of that required to overcome friction is necessary to bring a 3200-pound automobile up to a speed of 30 miles an hour in a distance of 242 feet?

10. A 2-ounce bullet is shot vertically into the air with a velocity of 1200 feet per second. How much and what kind of energy does it

have (*a*) as it leaves the gun? (*b*) 10 seconds later? (*c*) when it reaches the highest point?

159. Transformation of energy. In nature kinetic and potential forms of energy are continually changing into one another.

Thus, when a pendulum bob (Fig. 191) is at the highest part of its swing *A*, it has potential energy because of its height *h*. As it swings down, this potential energy disappears; but the bob gains speed, and at *B* its energy is all kinetic. As the bob swings up again on the other side *C*, its velocity and kinetic energy decrease, but its potential energy increases. At *C* its energy is all potential and equal to that at *A*, if there are no losses due to friction.

Similarly, when the hammer of a pile driver is at its highest position, its energy is all potential. When it hits the pile, it has lost this potential energy, but has gained an equal amount of kinetic energy.

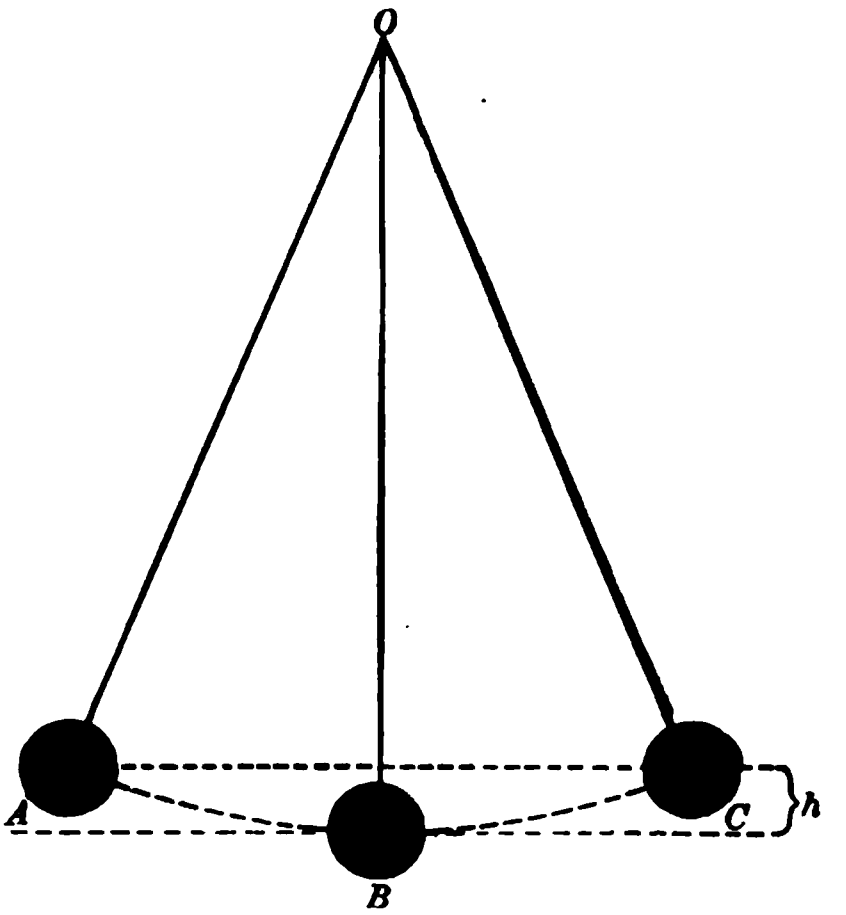

Fig. 191. Transformation of energy in a pendulum.

160. The conservation of energy. As these examples indicate, energy is *never made from* anything that is not energy, or *turned into* anything that is not energy. The total quantity of energy in the universe is always the same and is changed only in form and distribution. In any given machine there may be leaks of energy because of friction, radiation, etc.; however, the energy that leaks away is not destroyed, but is given as heat to the surroundings of the machine.

Thus, in the pendulum (Fig. 191) the sum of the kinetic and potential energies is the same wherever it is in its swing, unless there is friction. If there is friction, some energy disappears as heat and less is left in the pendulum; but the total energy is unchanged.

Whenever one form of energy disappears, other forms appear in equivalent amounts. This fact, *that energy can never be manufactured or destroyed, but only transformed or directed in its flow*, was first stated (not very clearly) by a German, Robert Mayer, and was firmly established by Helmholtz. It is called the LAW OF THE CONSERVATION OF ENERGY and has become the most important generalization in all physics.

161. Dissipation of energy. When energy is used or transformed, although none is ever destroyed, there is always a loss of another kind. Thus when mechanical energy is used to drive a machine and the machine in turn does work, as in lifting something, the output of the machine is less than the input because of friction. The balance of the energy put in is changed into heat, and diffused or dissipated, so that it is no longer *useful* energy. The loss is not in the total quantity of energy in the world, but in the usefulness or availability of some of it. The same is true whenever mechanical or chemical energy is changed into electrical, or when electrical or thermal energy is changed into mechanical. Lord Kelvin (Fig. 192) was one of the first to recognize the general principle that *whenever energy is used or transformed, some of it slips from our control and becomes forever dissipated and unavailable.*

Fig. 192. Lord Kelvin (Sir William Thomson, 1824-1907). Professor of physics in Glasgow University for more than fifty years. Eminent electrical engineer. Made Atlantic cables work. A pioneer in the development of thermodynamics.

SUMMARY OF PRINCIPLES IN CHAPTER IX

Energy of a body is its capacity for doing work.

Units of energy same as units of work.

Potential energy $= Wh$.

Kinetic energy $= \frac{Wv^2}{2g}$.

The conservation of energy: Energy can never be manufactured or destroyed, but only transformed or directed in its flow.

QUESTIONS AND PROBLEMS

1. Trace the transformations of energy in the process of firing a gun.

2. Trace the transformations of energy when water from a mill pond drives an overshot water wheel and the power obtained is used to run a sawmill.

3. In what form is energy supplied to a man? to a horse? to an automobile? to a locomotive?

4. The pendulum of a clock would die down because of the friction of the air around it if energy were not continually supplied to it. How is this done?

5. A certain rifle was once described in the headline of a magazine advertisement as striking "a blow of 2038 pounds." Farther down in the advertisement it appeared that the bullet weighed $\frac{1}{35}$ of a pound, and that its velocity was 2142 feet per second. What did the headline mean?

6. A 1-pound ball falls for two seconds and rebounds a distance of 50 feet. How much mechanical energy has the ball lost? What has become of the lost energy?

PRACTICAL EXERCISE

Perpetual-motion machines. Consult an encyclopedia on perpetual-motion machines. Describe how some of them are supposed to operate and explain the fallacy in their construction.

CHAPTER X

HEAT—EXPANSION AND TRANSMISSION

Thermometer scales — linear and volumetric expansion of solids — expansion of liquids — maximum density of water — expansion of gases — the absolute scale — pressure coefficient of gases — gas equation — hot-air engine — convection currents — heat transfer by convection — heating and ventilating systems — conduction — saving heat — radiation — molecular theory.

Expansion by Heat

162. Sources of heat. Our most important source of heat is the **sun.** The more nearly vertical the sun's rays are, the more heat they give. This explains why we receive more heat at noon than in the morning or evening, more heat in summer than in winter, and more heat near the equator than near the poles.

The **interior of the earth** is hot. Hot springs and volcanoes indicate this. Also in mine shafts sunk into the earth the temperature rises about one degree for every hundred feet of depth.

To warm our houses and run our engines, we do not as yet depend directly on the sun or on the internal heat of the earth, but on the heat produced in **burning** wood, coal, oil, or gas. The heat thus obtained comes indirectly from the sun, having been stored as chemical energy in plants in past ages.

Electricity is coming to be more and more a convenient source of heat which can be localized at any desired point, as in an electric soldering iron, a toaster, a flatiron, or an electric range. Electric ovens are used to bake the enamel paint on machinery, and electric furnaces to prepare and refine metals.

We shall discuss the heating effect of electric currents in Chapter XVI.

We have already learned in our study of machines and in our everyday experience that **friction** produces heat. For example, in scratching a match, in using drills, saws, and files, indeed, whenever mechanical energy is apparently lost, we find that heat appears.

John Tyndall (1820–1893) in his lectures on "Heat considered as a mode of motion" used to perform a striking experiment to show that friction produces heat.

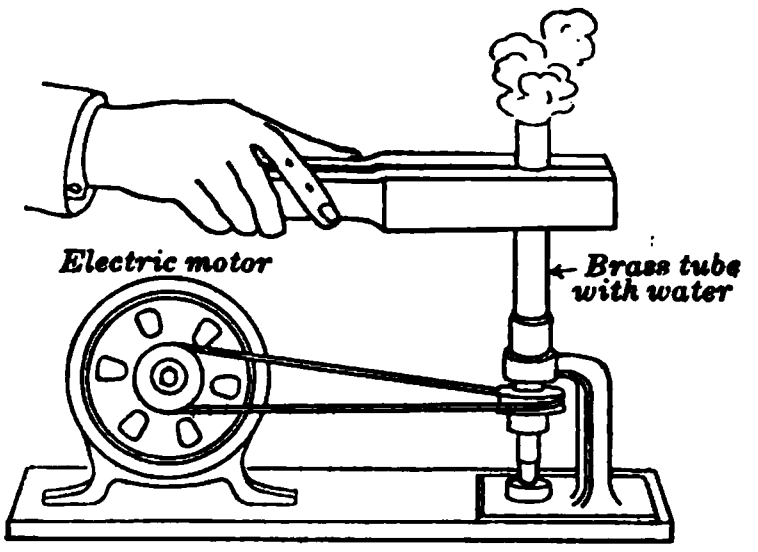

Fig. 193. Friction on the rotating tube boils the water within.

Let us try the same experiment by putting a little water in a metal tube (Fig. 193). If we close the tube with a stopper and rotate it with a motor, we find that the friction between the rotating tube and a wooden clamp generates in a few minutes enough heat to boil the water and blow the stopper out.

163. The thermometer. A deep cellar seems cold in summer and warm in winter, even though it remains at nearly the same temperature. A room often seems hot after we have been out in the cold, although it seems chilly after we have been in it awhile. Our sensations about the temperatures of things are therefore very unreliable and depend on our own condition at the moment. So it is necessary to have some kind of instrument to indicate accurately how hot or cold things are; that is, a **thermometer.** The usual form of thermometer is based on the fact that most liquids, such as mercury and alcohol, expand when being heated and contract again on cooling.

164. Making a mercury thermometer. A spherical or cylindrical bulb is blown on one end of a piece of glass tubing with a very fine uniform bore, and the bulb and part of the stem are filled with mercury. When the mercury is warmed, it expands and rises in the stem until

it overflows. Then the top of the tube is closed by melting the glass. When the mercury cools again, it leaves a vacuum in the top of the tube. If the bulb is now placed in the steam from boiling water, the mercury rises to a definite point on the stem, which is marked with a scratch. This point is called the **boiling point.** If the thermometer is then put in melting ice, the mercury goes back down the stem and stops at a definite point. This point is called the **freezing point.**

165. Centigrade and Fahrenheit scales. In thermometers that are used for scientific work the distance on the stem between these two fixed points is divided into 100 equal spaces, called degrees (Fig. 194). In this thermometer, which is called a **centigrade** thermometer, the **freezing point** is marked **zero** and the **boiling point** is marked **one hundred.** When the divisions extend below the zero point, they are called degrees below zero, or minus degrees.

Among English-speaking people a scale devised by **Fahrenheit** in 1714 is in common use. On this scale the freezing point is marked 32 degrees (32°) and the boiling point 212°, so that the portion between the freezing and boiling points is divided into 180 equal spaces (Fig. 194). Since *100 divisions on the centigrade scale are equivalent to 180 divisions on the Fahrenheit scale*, one division centigrade is equivalent to $\frac{9}{5}$ divisions Fahrenheit. To change a temperature expressed on the centigrade scale to the Fahrenheit scale, we have to remember that *0° F. is 32 Fahrenheit degrees below 0° C.*

Fig. 194. Scales of centigrade and Fahrenheit thermometers.

FOR EXAMPLE, 68° F. is 68 − 32, or 36 Fahrenheit degrees above the freezing point; and 36 Fahrenheit degrees are equivalent to $\frac{5}{9} \times 36$, or 20 centigrade degrees. Since the freezing point is 0° C., then 20 centigrade degrees above this point is 20° C. Therefore 68° F. is equivalent to 20° C.

To change a Fahrenheit reading to centigrade, or *vice versa*, we may use the equation:

$$\tfrac{5}{9}(F - 32) = C.$$

Inasmuch as mercury freezes at $-39°$ C., the thermometers used for very low temperatures contain alcohol, which is usually colored red or blue.

166. Special thermometers. Thermometers are made in many special shapes and with special protecting cases for specific purposes, such as bath thermometers, milk thermometers, incubator thermometers, thermometers for candy making, thermometers to screw into the sides of heaters or steam pipes, and thermometers specially designed for scientific work. None of these thermometers differ in principle from each other.

One type, however, of great importance in the household, is made with a special device that everyone should understand. In the clinical thermometer (Fig. 195), which is put under the tongue of a sick person to detect fever, there is a little constriction in the bore of the mercury tube just above the bulb. When the mercury expands, it crowds past this constriction and rises in the stem in the usual way. When the thermometer is taken out of the patient's mouth to be read and cools off again, the mercury column breaks at the constriction instead of running back down the stem, and continues to indicate the maximum temperature reached.

Fig. 195. Fever, or clinical, thermometer.

QUESTIONS AND PROBLEMS

1. Change to centigrade: 70° F., 150° F., 0° F., $-10°$ F.

2. Change to Fahrenheit: 15° C., 500° C., $-26°$ C., $-190°$ C.

3. What would a rise in temperature of 80° on the centigrade scale be in Fahrenheit divisions?

4. The temperature of the air on a certain day was 90° F. at noon and 45° F. late the next night. What was the "drop" in centigrade degrees?

5. At what temperature do a centigrade and a Fahrenheit thermometer read the same?

6. How do primitive people start a fire?

7. Why do sparks fly from car wheels when the brakes are quickly applied?

8. Why must a tool be kept wet with cold water when being sharpened on a grindstone?

9. If one wants the division marks far apart on the stem of a thermometer, what must be the relative size of bulb and stem?

10. Every clinical thermometer should be washed carefully before and after using. Should hot or cold water be used? Why?

11. How is the mercury column of a clinical thermometer brought down again after it has been read?

Practical Exercises

1. Maximum and minimum thermometer. Explain the action of the "maximum and minimum" thermometer illustrated in figure 196. For what would such a thermometer be used?

2. Temperature of the body. After violent physical exercise one feels very hot. Is the body temperature higher than normal? Try it.

167. Expansion by heat — solids. When a railroad track is built, gaps are usually left between the ends of the rails, to allow for the expansion of the steel in summer. Iron rims are placed on wheels while hot, because they are then bigger and can be easily slipped on. When they cool, they contract and hold fast to the wheel. An ordinary wall clock loses time in summer because its pendulum expands a little and so swings more slowly. Almost all solids expand more or less when heated, but this expansion is so very small that one must take special pains to see it.

Fig. 196. Maximum and minimum thermometer.

When solids expand and contract, they may exert enormous forces. We can show in a striking way the force exerted by the

expanding and contracting of a metal bar in the following experiment.

In the apparatus shown in figure 197 there is a metal bar which is heated by a series of little flames below. The expansion, although

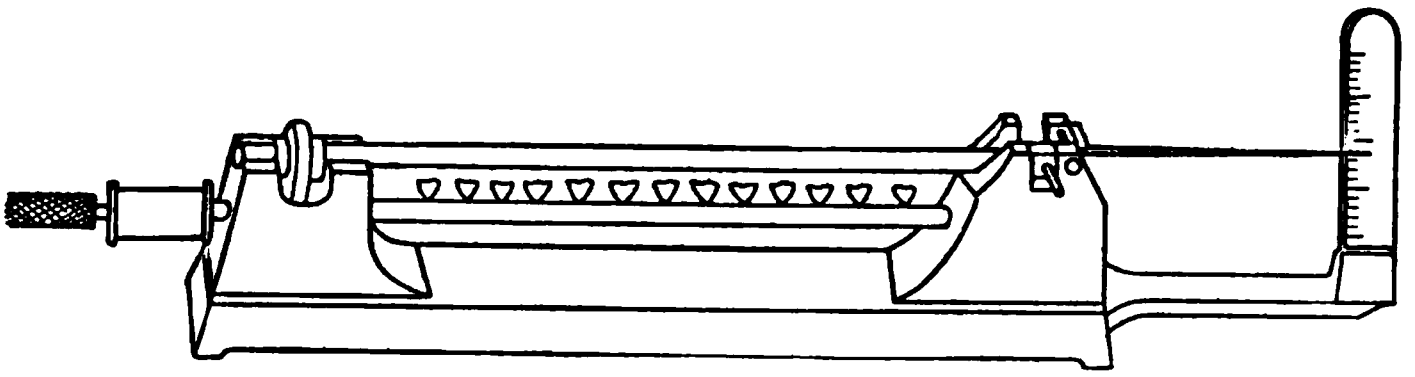

Fig. 197. Force exerted by expansion and contraction of metal bar.

very slight, is magnified by the bent lever at the end; as the bar gets hot, the pointer rises.

To show that large forces are exerted by an expanding or a contracting body, we put a steel rod through a hole in the bar near where the pointer touches it, and adjust the nut at the other end until the rod rests against the further side of the slot in the frame. If we then heat the metal bar, the steel rod suddenly breaks and the pointer is thrown violently up. Then we put another steel rod through the hole, adjust the nut to bring the rod against the nearer side of the slot, and allow the bar to contract. The steel rod snaps again and the pointer is thrown violently down.

168. Unequal expansion of metals. Careful experiments show that different metals expand at different rates. Thus, platinum expands less and zinc more than other common metals. If we made a platinum meter rod correct at 0° C., it would be 0.9 millimeters too long at 100° C. Similarly a steel meter rod would be 1.3 millimeters too long, and a zinc meter rod would be 2.9 millimeters too long.

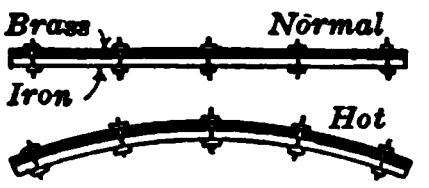

Fig. 198. Effect of heating a compound metal bar.

If two different metal strips, such as iron and brass, are riveted or welded together (Fig. 198), forming a **compound bar**, the bar when heated will bend or curl, because of the unequal expansion of the metals.

A compound bar of this sort is the essential part of most "**metallic thermometers.**" A long bar is coiled in a spiral and one end is held fast, the motion of the other end being magnified and transmitted to a pointer. In a recording thermometer (Fig. 199) a paper disk is rotated once a day or once a week by clockwork, and a continuous record of the temperature is made by a pen at the end of the pointer.

The motion of the free end of a compound bar can be made, not merely to indicate, but to control, the temperature of an inclosed space; such a device is called a **thermostat.**

Fig. 199. Recording thermometer. The chart is rotated by clockwork.

In one type of thermostat, often used in chicken incubators, the compound bar raises or lowers a light damper that controls the intake of warm air from the heating lamp. In another type, used to control electric heating, the motion of the free end of the bar makes or breaks the current.

169. Measurement of expansion. In considering how much a given object — such as a steel rail — will expand, it is necessary to know three things about it, namely, *its length*, *the rise in temperature*, and *the rate of expansion* of the particular substance used.

FOR EXAMPLE, if we know that a steel rail is 33 feet long and each foot of it expands 0.000010 feet per degree centigrade, we can compute how much it will expand from winter to summer, a range of perhaps 50° C. The expansion is equal to the expansion per degree for one foot, multiplied by the length in feet and by the rise in temperature. That is,

$$\text{Expansion} = 0.000010 \times 33 \times 50$$
$$= 0.0165 \text{ feet} = 0.198 \text{ inches.}$$

In symbols,

$$e = kl\,(t' - t)$$

where e = expansion, or change in length,
k = expansion per degree, per unit length,
l = length,
t' = temperature when hot,
t = temperature when cold.

The *factor* k, called the **coefficient of linear expansion,** *is the expansion of a unit length for 1 degree rise in temperature.* It is a very small fraction, and varies with different substances. Notice that no matter in what unit the length l is expressed, the expansion e will come out the same. Why? Usually k is given per degree centigrade, but the coefficient for the Fahrenheit scale can be computed by multiplying by $\frac{5}{9}$. Why?

The coefficients per degree centigrade of some common substances are given in the following table:

Zinc	0.000029	Cast iron	0.000011
Lead	0.000029	Steel	0.000010
Aluminum	0.000023	Platinum	0.000009
Tin	0.000022	Glass	0.000009
Silver	0.000019	Pyrex glass	0.0000032
Brass	0.000019	"Invar" (nickel steel, 36% Ni)	0.0000009
Copper	0.000017		

170. Some illustrations. In the construction of a steel bridge allowance has to be made for the expansion of the steel. For example, in the great bridge over the Firth of Forth in Scotland, which is more than a mile and a half long, the total allowance for expansion is 6 feet. In steam plants long pipes are provided with sliding or "expansion" joints, unless the bends in the pipe are such as to yield enough for the expansion.

When a lamp chimney is heated, the glass expands. If a drop of water strikes it, the glass in the immediate vicinity cools rapidly and pulls away from the rest, and the chimney cracks.

Quartz is made into objects that are as clear as glass, but have so small a coefficient of expansion (0.0000005) that a red-hot quartz crucible may be suddenly thrust into water without cracking.

The pendulum rod of a clock is often made of dry wood, which expands very little. It is, however, affected by moisture; so for accurate clocks some kind of compensated metallic pendulum is used. One form of compensated pendulum is that commonly seen in French clocks. It consists of a glass tube or tubes filled with mercury (Fig. 200), suspended by a steel rod. When

Fig. 200. Compensated mercury pendulum.

the temperature goes up, the raising of the center of gravity of the mercury, due to its expansion, is equal to the lowering of the whole reservoir of mercury, due to the expansion of the steel rod, so that the effective length of the pendulum remains constant.

In a watch, the balance wheel if uncompensated will run slower in hot weather because the hairspring has less elasticity at a higher temperature, and also because the expansion of the radius of the wheel carries the rim farther from the center, and so slows down its rotation. The rim is therefore made of two strips of metal, brass on the outer edge and steel on the inner, fastened with screws as shown in figure 201. When the temperature rises, the free ends of the rim curl inward, thus bringing part of the rim nearer the axis. This compensates for the expansion of the crossbar and the weakening of the hairspring.

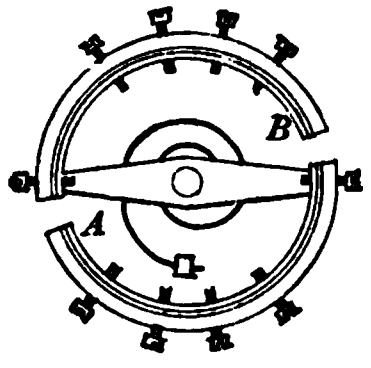

Fig. 201. Balance wheel of a watch.

QUESTIONS AND PROBLEMS

1. A brass meter bar is correct at 15° C. What will be the error at 20° C?

2. A steel rail 33 feet long is found to expand 0.275 inches when heated from −17° F. to 100° F. What is the coefficient of linear expansion on the Fahrenheit scale, and also on the centigrade scale?

3. The steel cables of Brooklyn Bridge are about 5000 feet long. How much do they change in length between a winter temperature of −20° F. and a summer temperature of 97° F.?

4. A steel shaft is heated to 65° C. while being shaped in a lathe, and its diameter at that temperature is made just 5 centimeters. What will its diameter be at room temperature (15° C.)?

5. A steel wire, 150 centimeters long at 15° C., becomes 151.3 centimeters long when an electric current is sent through it. How hot does it get?

6. A 100-foot steel tape is standard length at 62° F. How many inches too long will it be at 100° F.?

7. Explain why pouring hot water on the neck of a bottle will sometimes loosen a glass stopper.

8. A thick glass milk bottle is more likely to crack when hot water is poured into it than a thin glass flask. Explain.

9. Washington monument at noontime bends a few hundredths of an inch. In what direction does it lean? Explain.

171. Cubical expansion of solids. A metal bar when heated expands, not only in length, but also in breadth and thickness; in short, its volume increases. This expansion in volume is called **cubical expansion.** Suppose we have a cube 1 centimeter on an edge, at a temperature of 0° C., and raise this to 1° C.; each edge of the cube will become $(1 + k)$ centimeters, k being the coefficient of linear expansion. The original volume, 1 cubic centimeter, will become $(1 + k)^3$ cubic centimeters. Now $(1 + k)^3$ equals $1 + 3\ k + 3\ k^2 + k^3$; but since k is a very small fraction, the value of $3\ k^2$ and k^3 will be so small that they may be neglected without appreciable error. The volume of the cube is, then, $1 + 3\ k$; hence the volume expansion per cubic centimeter per degree is $3\ k$ cubic centimeters, and *the coefficient of cubical expansion is three times the coefficient of linear expansion.*

FOR EXAMPLE, the coefficient of linear expansion of glass is 0.000009, and the coefficient of cubical expansion is 3 times 0.000009, or 0.000027. A flask which held just a liter at 0° C. would hold 1002.7 cubic centimeters at 100° C.

172. Expansion of liquids. Let us fill a small round-bottomed flask with water colored with ink and insert a stopper with a glass tube and paper scale (Fig. 202). Then let us put the flask into a jar of ice water and mark on the scale the position of the liquid in the tube. If we now put the flask into a basin of boiling water, we note at first a sudden drop of the liquid in the tube (why?) and then a rapid rise. Evidently the liquid expands more than the glass.

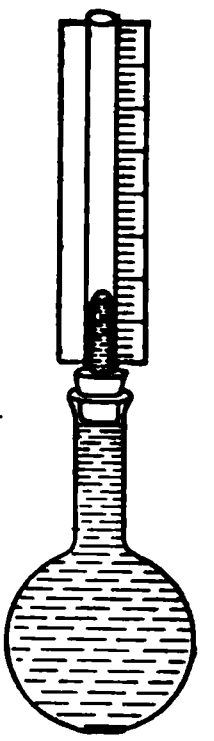

Fig. 202. Expansion of a liquid.

In general, it is found that liquids expand much more than solids. For example, when a liter of water is heated from 0° to 100° C., it increases in volume about 43 cubic centimeters, whereas a block of steel of the same volume would expand only 3 cubic centimeters. Mercury, and many organic liquids such as ether, alcohol, oils, and especially kerosene expand even more than water.

Liquids, like solids, expand with almost irresistible force when heated, and exert enormous pressures if expansion is prevented by their surroundings.

In the case of liquids and gases, cubical expansion rather than linear is always measured. Since, however, the vessel which contains the liquid expands as well as the liquid, we observe only the *apparent* expansion. In a mercury thermometer the apparent expansion is only about $\frac{5}{6}$ of the real expansion of the mercury.

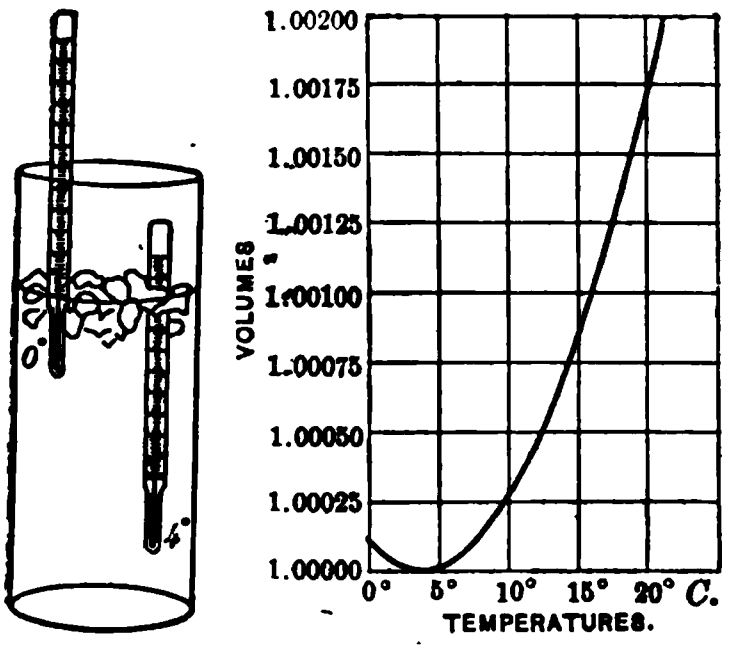

Fig. 203. Maximum density of water at 4°C.

The coefficient of cubical expansion is the expansion per unit volume for 1 degree rise in temperature. For example, the coefficient of cubical expansion of alcohol is 0.00104 and of mercury 0.000182.

173. Abnormal behavior of water. We have just seen that solids and liquids expand as a rule when heated; water does the same except near its freezing point.

If we fill a tall glass jar nearly full of cracked ice (Fig. 203) and let it stand for a while, the temperature of the water near the top comes to 0° C. and remains so, while the temperature at the bottom is about 4° C. Since the heaviest liquid stays at the bottom, this means that water at 4° C. is denser than water at 0°.

Very precise measurements show that *water is most dense at 4° C. When water at 4° C. is either warmed or cooled, it expands and becomes lighter*, as shown by the curve in figure 203.

This fact is important in that otherwise the water in lakes would freeze in winter, not merely at the surface, but solidly from top to bottom, thus destroying all aquatic life.

174. Expansion of gases. We may easily demonstrate the great expansion of a gas when heated, with the apparatus shown in figure

204. Even the heat of the hand on the flask causes bubbles of air to be expelled from the tube and to rise through the water. If the heat of a flame is applied to the flask, the bubbles rise rapidly. If after a time the flame is removed and the flask allowed to cool, water rises into the flask to take the place of the escaped air. From the volume of water thus drawn up into the flask, it is evident that a considerable fraction of the air was expelled during the expansion.

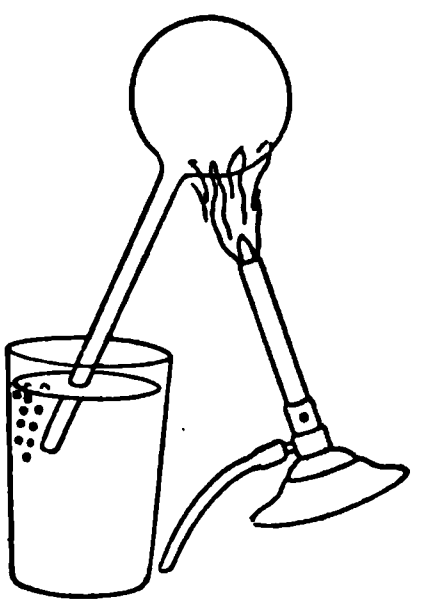

Fig. 204. A gas expands when heated.

The expansion of gases, such as air, illuminating gas, or hydrogen, is remarkable for two reasons: first, because it is so large (about nine times as much as for water), and second, because it is nearly the same for all gases.

The coefficient of expansion of a gas can be measured in a rough way as follows. Suppose we have a tube of uniform bore (Fig. 205) which is closed at one end and has a little pellet of mercury to separate the inclosed gas AB from the atmosphere. (Dry air is a good gas with which to experiment.) If we put the tube in a freezing mixture at 0° C., the gas in the tube will contract, and we can measure the length AB, which we shall assume to be 273 millimeters. If we put the tube in steam at 100° C., the gas will expand and we can measure its length again. This length AB' we shall find to be about 373 millimeters. From this experiment we see that the air expanded 1 millimeter for each degree rise in temperature (the expansion of the glass can be neglected). That is, the gas expanded $\frac{1}{273}$, or 0.00366 of its volume at 0° C. for each degree rise in temperature.

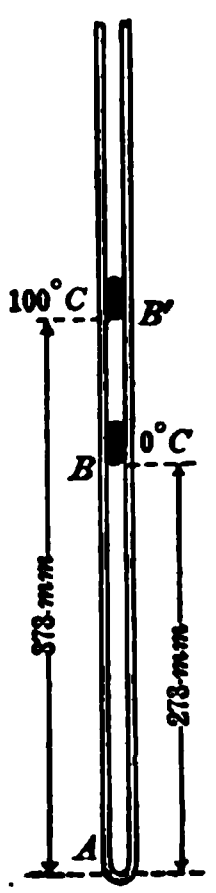

Fig. 205. Expansion of a gas under constant pressure.

In general, *different gases have nearly the same coefficients of expansion, namely,* $\frac{1}{273}$, *or 0.00366.*

175. Absolute temperature scale. In the experiment just described we started with an air column 273

millimeters in length at 0° C.; if we had cooled the gas from 0° to −1° C., the length *AB* would have been shortened a millimeter; and if we had cooled it to −10° C., the length of the air column would have become 263 millimeters. If, then, the air column continued to contract at the same rate if cooled indefinitely, the volume of the air at −273° C. would become zero. As a matter of fact, we can never get a gas to so low a temperature as −273° C., because every known gas turns into a liquid before that temperature is reached. The temperature **−273° C.** is, however, one of unusual interest in the study of gases. It is called the **absolute zero**, and temperatures measured from this point as zero are called **absolute temperatures.** Absolute centigrade temperatures may be designated by the letter A. Thus, 0° C. = 273° A., 50° C. = 323° A., and 100° C. = 373° A. *To change any temperature from the centigrade to the absolute scale* (Fig. 206), *add 273 degrees.* If we represent temperatures in the centigrade scale by t and on the absolute scale by T, we have

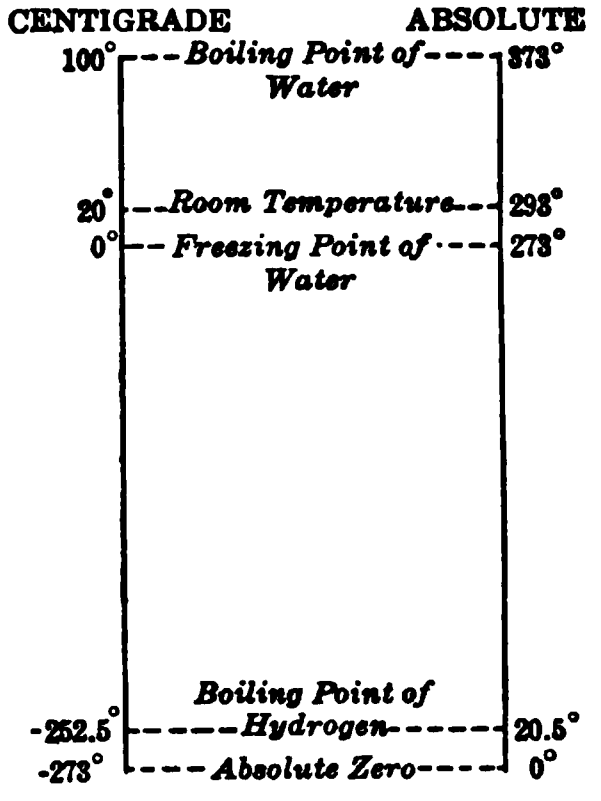

Fig. 206. Centigrade and absolute-temperature scales.

$$T = t + 273.$$

176. The law of Charles. A little more than a hundred years ago a Frenchman, Charles, studied the expansion of gases and found that all gases expand and contract to the same extent under the same changes of temperature, provided there is no change in pressure.

In general, *when the pressure is kept constant, the volume of gas is very nearly proportional to its absolute temperature.* This is known as the **law of Charles.**

This relation between the volume and temperature of a gas at constant pressure can be very concisely expressed by the equation:

$$\frac{V}{V'} = \frac{T}{T'} \qquad \text{(I)}$$

when V and V' represent the volumes of a certain quantity of gas at the same pressure but at different absolute temperatures, T and T'.

From the above discussion of absolute temperature it will be seen that the volume of any gas is doubled when its temperature is raised from 273° A. (0° C.) to 2 × 273°, or 546° A. (273° C.).

FOR EXAMPLE, suppose we have a quantity of gas which occupies 320 cubic centimeters when the temperature is 15° C. What volume will it occupy at 0° C.?

First change the centigrade temperatures given in the problem to absolute temperatures by adding 273; then

$$\frac{V}{320} = \frac{273}{273 + 15}$$

$$V = \frac{320 \times 273}{288} = 303 \text{ cm}^3.$$

In solving such problems it is advisable to compare the result obtained by computation with the original volume to see whether it is reasonable. Thus, if the gas is measured under laboratory conditions when the temperature is 20° C., the volume of the gas under standard conditions (0° C.) would be about 7 per cent *less*.

PROBLEMS

1. What volume would 160 cubic centimeters of hydrogen, measured at 17° C., occupy at 0° C.?

2. If 250 cubic feet of illuminating gas were measured at −10° C., what would the volume be at 20° C.?

3. The weight of 22.4 liters of oxygen at 0° C. is 32.0 grams. What would be the volume of the same quantity of oxygen at 25° C.?

4. At what temperature would the volume of a given quantity of gas be exactly twice what it is at 17° C., the pressure remaining constant?

5. A liter of air at 0° C. and atmospheric pressure weighs 1.293 grams. What is the density of air at 100° C. and atmospheric pressure?

6. The coefficient of expansion of gasoline is about 0.0006 per degree Fahrenheit. If a tank car contains 100,000 gallons of gasoline at 60° F., how much shrinkage in volume will occur when the temperature drops to 0° F.?

177. Pressure coefficient of gases. Since the volume of a gas increases as the temperature rises, it is reasonable to expect that if a certain quantity of gas were heated and yet confined in the same space, the pressure would increase. Very careful experiments have been carried out to determine the **pressure coefficient** of a gas, and the results show that *the pressure of a gas kept at constant volume increases for each degree centigrade very nearly* $\frac{1}{273}$, *or 0.00366 of the pressure at 0° C., no matter what the gas is.* It will be noticed that this is the same fraction which we found for the increase of *volume* at constant pressure.

It will be more convenient to state this in terms of absolute temperature, thus: for all gases at constant volume, *the pressure is proportional to the absolute temperature*, or

$$\frac{P}{P'} = \frac{T}{T'}. \qquad \text{(II)}$$

FOR EXAMPLE, an automobile tire is pumped up to a pressure of 70 pounds per square inch when the air is at 17° C. After driving the car on a hot day, the temperature of the air in the tube is 57° C. What will the pressure become if we assume that the tube does not stretch?

$$\frac{70}{P'} = \frac{273 + 17}{273 + 57}$$

$$P' = \frac{330 \times 70}{290}$$

$$= 79.8 \text{ lbs. per sq. in.}$$

178. The gas equation. The relation between the volume and pressure of a gas at constant temperature may be concisely expressed by Boyle's law (section 102) thus:

$$PV = P'V' \qquad \text{(III)}$$

where V is the volume of a given quantity of gas under pressure P, and V' is the volume of the same gas under a pressure P', the temperature in the two cases being the same.

The relation of the volume to both pressure and temperature can be expressed by the **gas equation,**

$$\frac{PV}{T} = \frac{P'V'}{T'}.$$

It will readily be seen that this equation reduces to equation III (Boyle's law) when $T = T'$, and that if $V = V'$ the equation becomes $P/T = P'/T'$, which is another form of equation II, and that if $P = P'$ the equation becomes $V/T = V'/T'$, which is another form of equation I (Charles' law).

FOR EXAMPLE, suppose we wish to find the volume of a certain quantity of gas under standard conditions, that is, at 0° C. and 760 millimeters pressure, when it is known to occupy 1200 cubic centimeters at 15° C. and under a pressure of 740 millimeters.

We have

$$\frac{1200 \times 740}{273 + 15} = \frac{V' \times 760}{273 + 0}$$

whence

$$V' = \frac{1200 \times 740 \times 273}{760 \times 288} = 1110 \text{ cm}^3.$$

QUESTIONS AND PROBLEMS

1. A steel tank full of air at 15° C. under atmospheric pressure was sealed and thrust into a furnace, where it was heated to 1000° C. How many atmospheres of pressure did the air then exert? Neglect the thermal expansion of the steel.

2. The pressure in the cylinder of an automobile engine just before the explosion may be 5 atmospheres absolute; after the explosion it may be 12 atmospheres absolute. If the explosion be thought of as an instantaneous warming of the gas in the cylinder, and if the temperature beforehand is 200° C., what is the temperature after the explosion?

3. A student in a chemical laboratory generates 50 liters of hydrogen at 10° C., and at a pressure of 700 millimeters. Find the volume of the gas under standard conditions; that is, at 0° C. and at 760 millimeters.

4. At the beginning of the so-called "compression stroke" in an automobile engine, its cylinder contains 42 cubic inches of gas and air at atmospheric pressure, and at a temperature of 40° C. At the end of the compression the volume is 12 cubic inches and the pressure is 5.5 atmospheres. What is the temperature?

5. At sea level the barometer stands at 76 centimeters and the temperature is 17° C., and on a mountain top the barometer stands at 40 centimeters and the temperature is −13° C. Compare the quantities of air in a cubic meter at the two places.

6. A liter flask contains 1.293 grams of air at 0° C. and 76 centimeters pressure. How many grams of air will it contain at 50° C. and 50 centimeters pressure?

179. Low and high temperatures. The investigations of Lord Kelvin and of other scientific men all point to the conclusion that the temperature −273° C. is really an **absolute zero** in the sense that it is **the lowest possible temperature in the universe.** Although no one has as yet succeeded in cooling a body to absolute zero, temperatures within a very few degrees of this point have been attained by the evaporation of liquefied gases. With liquid air, temperatures as low as −200° C. may be obtained, and with liquid hydrogen −258° C. Professor Onnes, at the University of Leyden in Holland, has found that the boiling point of liquid helium is −268.6° C., or only about 4.5° above the absolute zero; and in 1921 he cooled liquid helium to a temperature in the immediate neighborhood of 1° above the absolute zero by boiling it at a pressure of 0.02 mm. At these low temperatures rubber and steel become as brittle as glass, and metals become much better conductors of electricity than at ordinary temperatures.

The temperatures which one finds in the furnaces used to melt metals are much higher than the temperature of boiling water. For example, iron melts at about 1100° C., platinum

at 1755° C., and tungsten at 3000° C. Very high temperatures are commonly obtained by means of the electric arc, which gives 3700° C. It is estimated that the sun's temperature may be as high as 6000° C. and that some of the stars may be at 50,000° C.

180. Hot-air engine. An interesting application of the expansion of gases is the hot-air engine. Its operation can be understood by studying figure 207. A loosely fitting plunger *A* moves up and down and thus shifts the air back and forth in the cylinder *C*, which is heated at the bottom and kept cool at the top. The working cylinder *C'* has a nicely fitting piston *B*.

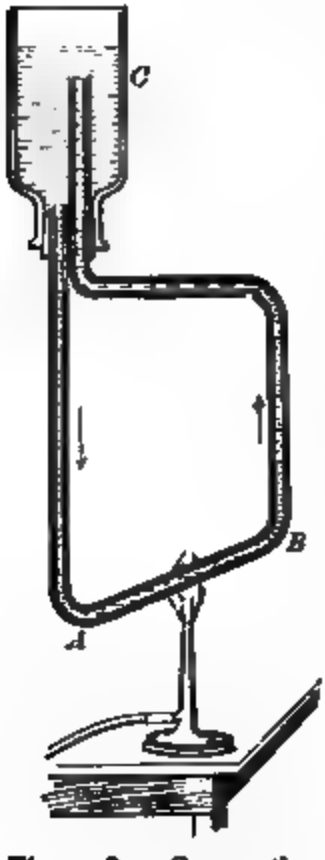

Fig. 207. Diagram of hot-air engine.

When the plunger *A* moves down, the hot air below is transferred to the top, where it is cooled. This makes it contract. The piston *B* is then forced down by the external pressure of the atmosphere. As soon as the piston *B* is near the bottom of its stroke, the plunger *A* is raised, causing the air to flow back under *A*, where it is heated by the fire. This makes it expand and forces the piston *B* up again, and then the cycle is repeated. Hot-air engines are sometimes used for pumping water on a small scale at isolated places, for they do not require expert attendants, and they use any kind of fuel. In general they cannot compete with gas engines on account of their bulk and the rapid wearing out of the heating surfaces.

Transmission of Heat

181. Convection currents. To make these clear, let us try two simple experiments.

Fig. 208. Convection current of water

We cut off the bottom of a bottle and bend a glass tube (Fig. 208) so that the ends can be slipped through a stopper which fits the neck of the bottle. If we invert the bottle and fill it with water containing a little sawdust, we can see a circulation of the

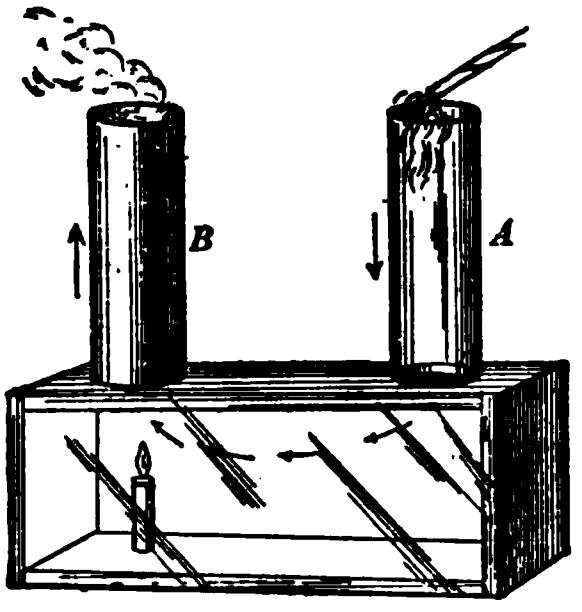

Fig. 209. Convection current of air.

water when a flame is waved back and forth from *A* to *B*. We note that the direction is from *A* to *B*. Why?

A box (Fig. 209) has a glass front and two holes in the top which are covered with glass chimneys. If we put a candle under one chimney, convection currents of air go down the cool chimney *A* and up the warm one *B*. A bit of lighted touch paper held near the top of the cool chimney makes the convection currents more evident.

All systems of heating and ventilation depend upon what are called convection currents, which in turn depend upon the expansion of liquids and gases. The explanation of the movement of convection currents is that any gas or liquid expands when heated, so that a given quantity of fluid increases in volume and consequently decreases in density. In a convection current, the lighter fluid is pushed up by the heavier surrounding fluid, just as a block of wood under water is pushed up by the surrounding water.

182. Heat transfer by convection. Since the up-going part of a convection current is warmer than the returning part, there is a transfer of heat from the flame, or other source of heat at the bottom, to the cooler parts of the circuit at the top. This process of transporting heat by carrying hot bodies or hot portions of a fluid from one place to another is called **convection.**

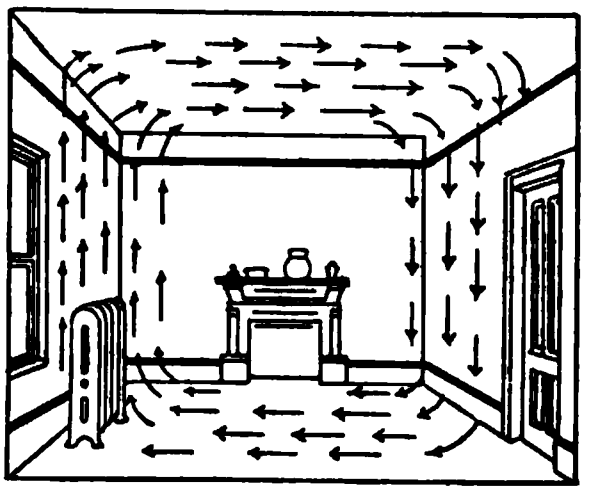

Fig. 210. Convection currents of air in a room.

The heating of a room by a radiator (Fig. 210) is an example of a useful convection current. The warm air in contact with the radiator rises, while the cooler air in other parts of the room flows in along the floor to take its place.

183. Draft in a chimney. To make anything burn, we must furnish a continuous supply of fresh air. For example, in a central-draft lamp (Fig. 211) there are holes in the base so that a current of fresh air can pass upward through the tube to supply the *inside* of the flame, and there are holes through the sides and bottom of the burner to supply fresh air to the *outside* of the flame. These currents are maintained by convection. The air inside the lamp chimney becomes warmer and therefore less dense than the outside air, and is pushed up by the entering fresh air.

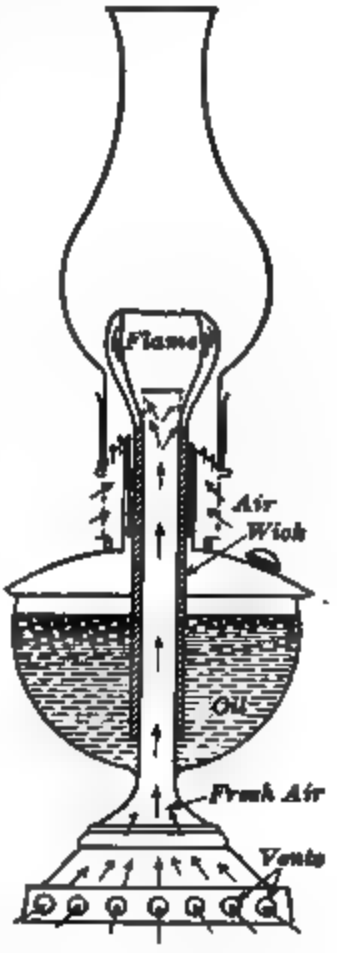

Fig. 211. Air currents in and about a central-draft lamp.

The draft in the chimney of a stove (Fig. 212) or a furnace is another example of a convection current. The hot gaseous products of the fire are pushed up the chimney by the cold heavier air which enters under the fire. The draft is not so strong when the fire is first lighted in a stove because the air in the chimney has not yet been heated. A strong draft is obtained by making a chimney as straight and smooth as possible; by extending it above other portions of the building; by keeping it away from an outside wall where it would cool off readily; and by making it double-walled, so as to keep the chimney gases warm all the way up. A chimney must not be so large that the hot gases cannot fill it; neither must it be so small as to impede ow. The chimneys used by factories are often very tall because the draft is due to the difference in total weight between the column of heated air and a similar column of outside air, and this difference is nearly proportional to the height of the chimney.

Fig. 212. Circulation of hot gases about the oven in a kitchen stove.

A great deal of heat is carried off by the hot gases in a chimney, but it must not be

supposed that this heat is all wasted. Devices, called economizers, have been invented to utilize this heat and to send comparatively cool gases up the chimney; but in such cases huge power-driven fans have to be used to produce the required draft. So we can say that the heat lost up a chimney is the price paid for the draft.

184. Hot-water heating. The arrangement for **heating water in the kitchen boiler** for general use in laundry and bathroom is shown in figure 213. The cold water enters the tank through a pipe which reaches nearly to the bottom. Water from the bottom of the tank is led to a coil of pipe heated by a gas flame or by the fire in the kitchen range. When this water becomes hot, it is pushed up and goes back into the tank at a point nearer the top. Thus a circulation is set up which continues until practically all the water in the tank has passed through the heating coil and the whole tankful is hot.

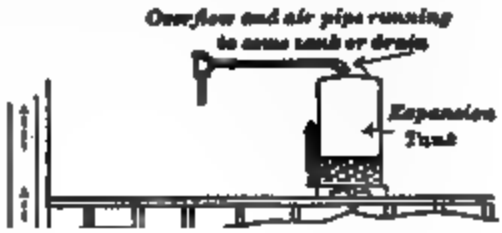

Fig. 213. Kitchen boiler for heating water.

The **hot-water system of heating houses** (Fig. 214) depends on this same principle of convection. Water is heated nearly to the boiling point in a furnace in the basement. The hot water is led from the top of the furnace through pipes to iron radiators in the various

Fig. 214. Hot-water system of heating houses.

rooms of the building. On account of the large exposed surface in each radiator, heat is rapidly given out by the hot water to the surrounding air. The cooled water is then carried from the radiators through return pipes to the base of the furnace. To prevent radiation from the pipes, a thick non-conducting coating of asbestos is often provided.

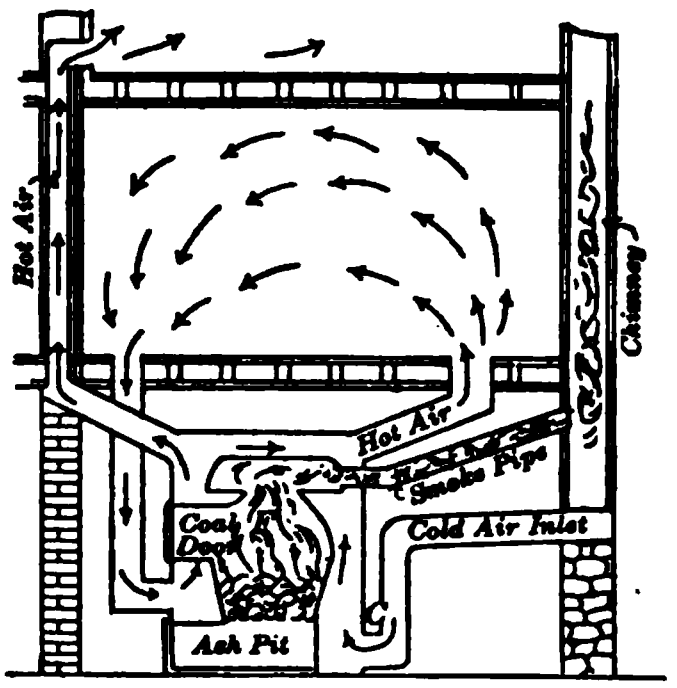

Fig. 215. Hot-air furnace with return flue.

185. Hot-air system of heating and ventilating. The **hot-air furnace** in the basement (Fig. 215) is simply a big stove, surrounded by a shell or jacket of galvanized sheet iron. The air between the stove and outer shell is heated and is then pushed up into the flues by the heavier cold air which comes in from out of doors through the cold-air inlet flue. The smoke, of course, goes up the chimney. Some of the warm air which enters the rooms escapes around the doors and windows; the rest is carried back to the base of the furnace by a return flue.

In the hot-water system of heating there is no provision whatever for changing the air in the room; that is, for **ventilation.** In the hot-air system a small quantity of fresh air is continually flowing into the rooms. This is enough for a private house. But in schools, churches, and other public buildings, large quantities of clean, fresh, warm air need to be continually supplied by other means. For the proper ventilation of a room it is estimated that each person in it requires about 50 cubic feet of fresh air every minute. In large modern school buildings the air is drawn in from out of doors by powerful fans, filtered through cloth, warmed by passing around steam pipes, and then distributed in ducts throughout the building. The vitiated air in each room is forced out through ducts near the floor. This

indirect system of heating, while expensive, furnishes excellent ventilation.

Questions and Problems

1. Why is an expansion tank necessary in a hot-water heating system?

2. Why is it essential to keep the flues of stoves and furnaces clean and free from soot and ashes?

3. Explain why opening the check draft in the smoke pipe of a stove slows up the fire.

4. Explain the purpose and operation of the damper in a kitchen stove (Fig. 212).

5. Why is the air in a room changed more quickly by opening a window at both top and bottom than if either half is opened alone?

Fig. 216. Water-cooling system for keeping automobile engines cool.

6. If 1 cubic foot of air at 0° C. weighs 0.081 pounds, how much will the air in a chimney 30 feet high and 1 foot square weigh if heated to 260° C.?

7. The chimney for a stove in an ordinary house is 30 feet in height and 9 inches square. If the average temperature of the flue gases within is 260° C. and the air outside is at 0° C., how many times heavier is a similar column of outside air than that within the chimney?

8. Why should all openings into a chimney be closed except those in actual use?

9. Figure 216 shows one type of cooling system (thermo-siphon) used for keeping automobile engines from becoming overheated. Explain how the principle of convection currents is illustrated here.

Practical Exercise

Model of a hot-water heating system. Set up a model of a hot-water heating system. This can be constructed from bottles, flasks, stoppers, and tubes found in any chemical laboratory. Demonstrate the operation of your model. For further details see *Good's* Laboratory Projects in Physics (Macmillan).

186. Conduction in solids. Besides *transporting* heat by carrying hot bodies about, or by making hot fluids flow through pipes, we can *transmit* heat without moving any material thing by either of two methods called **conduction** and **radiation.**

Everyone knows that the handle of a silver spoon gets hot when its bowl is in a cup of hot tea or coffee. If one end of an iron poker is put in the fire, the other end, unless provided with a wooden handle, soon burns one's hand. Yet if a wooden rod is plunged into a fire, it is hard to feel any warmth at the other end. So we conclude that silver and iron conduct heat better than wood. In general, metals are good conductors of heat.

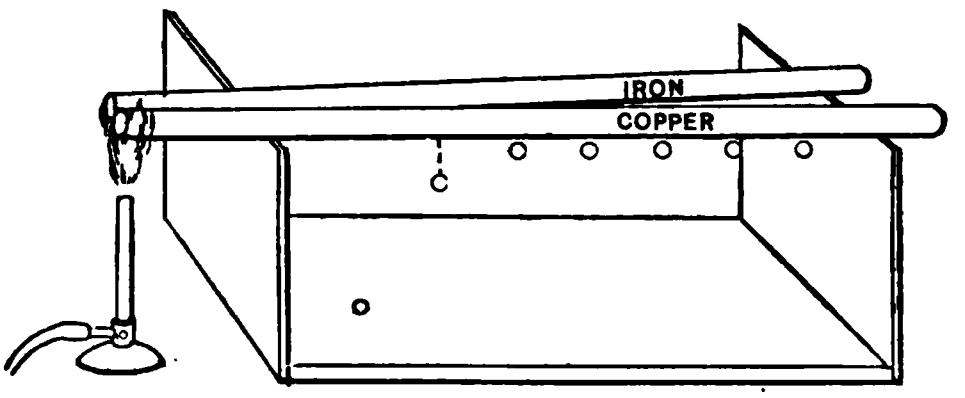

Fig. 217. Relative conductivity of copper and iron.

There are some substances, such as stone, glass, wood, wool, fur, and ashes, which are poor conductors of heat and are therefore called heat **insulators.** The metals, such as silver, copper, brass, iron, lead, etc., are good **conductors** as compared with the non-metals. Careful study shows that even the metals vary in their power to conduct heat, that is, in conductivity. This can be shown by the following experiment.

Let us fasten with sealing wax a number of steel balls at regular intervals on the under side of two rods, one of copper and one of iron. If we heat one end of each rod in a flame (Fig. 217), the balls on the copper rod soon drop off, beginning near the flame. Later the balls on the iron rod begin to drop off. Often half the balls will have dropped from the copper rod before the first one drops from the iron rod.

187. Conduction in liquids and gases. Liquids and gases are much poorer conductors than metals. This can be shown by the following experiment.

Let us take a large test tube full of water and place in it a few pieces of ice, which are held near the bottom by a wire grid, as shown in figure 218. Then we may boil the water at the top of the tube for some time without melting the ice in the bottom.

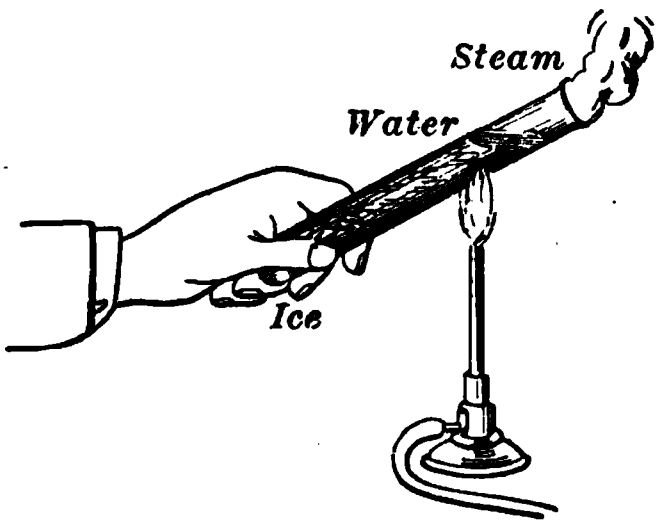

Fig. 218. Water is such a good heat insulator that ice and boiling water may be in the same test tube.

Experiments to measure conductivity show that iron conducts 100 times as well as water, and that water conducts 25 times as well as air.

It is an interesting fact that substances which are good conductors of heat are good conductors of electricity as well.

188. Applications. These differences in conductivity explain why pokers and teapots have wooden or insulated handles; why a vacuum bottle (Fig. 219) keeps things hot or cold a long time; and why we wear woolen clothing in winter. Woolen clothing of loose texture, furs, feathers, and eiderdown quilts are effective as heat insulators, because much air is inclosed in their pores and yet convection currents are prevented.

Differences in conductivity also account for many curious sensations of heat and cold. Thus in a cool room some things feel much colder than others. Metallic objects, which are good conductors, take heat rapidly from the hand, and so give the sensation of cold. Other objects such as wood and paper, carry off the heat of the hand slowly and so do not feel cold. Similarly, a piece of metal lying in the hot sun feels much warmer than a piece of wood beside it.

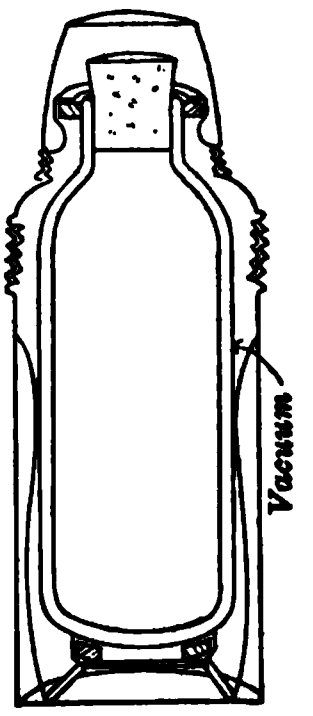

Fig. 219. Section of a vacuum, or thermos, bottle.

189. Saving heat. Since the saving of heat means, in general, the saving of fuel, the conservation of heat is

a question of national economy. Heat always tends to pass from warmer objects to cooler ones and can never be entirely retained. Nevertheless a knowledge of the properties of heat insulators makes it possible to save much heat which would otherwise be lost. For example, the walls of steel passenger cars are lined with a layer of heat insulating material, because the steel is so good a conductor of heat that such cars would waste too much heat in winter. For the same reason the walls of a house are built with an air space, as shown in figure 220. Double windows in winter, by forming a dead-air space, save large amounts of heat. Better insulation around a furnace or heater and around the pipes through which heat is distributed to various parts of a house often pays for itself in a short time by saving coal. In industrial plants steam pipes should be well insulated with asbestos or magnesia for the same reason. Much heat is wasted in dwellings by allowing currents of warmed air to escape through open fireplaces; dampers in the chimney throats above fireplaces should be kept closed when the fireplaces are not in use. In cold weather the cold-air intake duct of a hot-air furnace should be kept nearly closed, the circulation through the furnace being maintained by one or more return flues from the house itself.

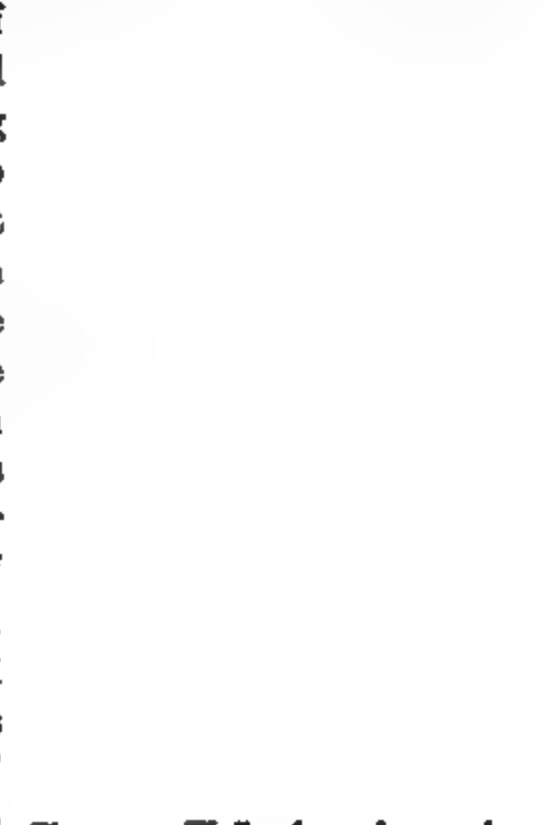

Fig. 220. Wall of a frame house showing air space.

Another important means of saving heat is the **fireless cooker** (Fig. 221). In this case a compartment, usually lined with sheet metal, is so thickly covered on all sides with some sort of insulating material that the contents once heated will stay hot

for many hours. A hot stone is often placed under the dish to act as a storage reservoir of heat.

Practical Exercise

Making a fireless cooker. Full directions may be found in Farmers' Bulletin 771, U. S. Department of Agriculture. How would you test its efficiency?

190. Radiation. If an iron ball is heated and hung up in the room, the heat can be felt when the hand is held *under* the ball. This cannot be due to convection, because the hot-air currents would rise from the ball. It cannot be due to conduction, because gases are very poor conductors. Similarly a lighted electric-light bulb feels hot if the hand is held near it, but when the light is turned off, the sensation stops very quickly. The glass of the bulb is a very poor conductor and there is practically no air left inside the bulb, so that the sensation of heat can be due neither to convection nor to conduction. Furthermore, an enormous quantity of heat comes to us from the sun. Yet men who make ascents in balloons and airplanes find that the air becomes less and less dense, so that it seems reasonable to suppose that the earth's atmosphere forms a coating only a few miles thick and that the space beyond is absolutely empty. So the sun's heat cannot come by convection or conduction.

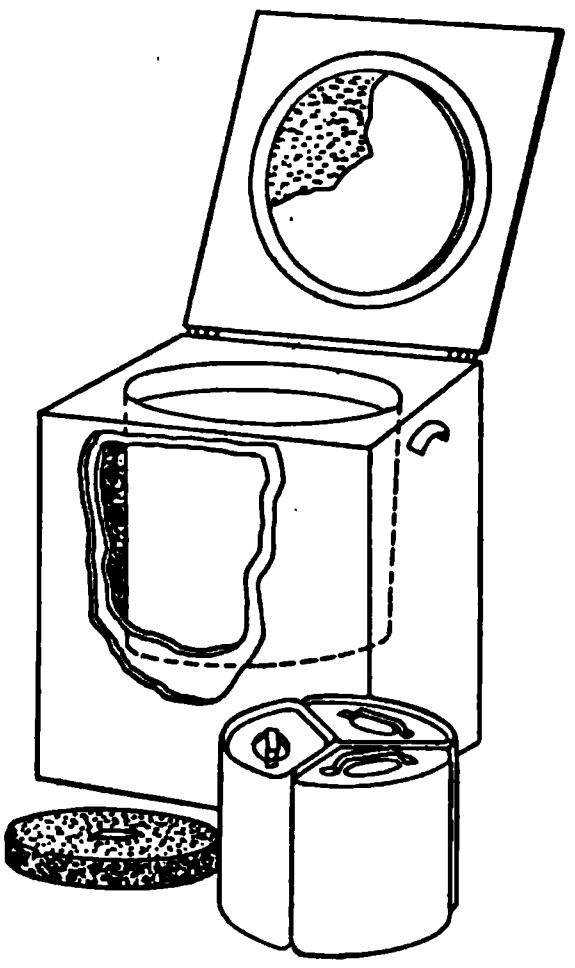

Fig. 221. Fireless cooker conserves heat.

To explain these phenomena, scientists have imagined a weightless, elastic fluid called **the ether** which fills all space and transmits heat and light by a process called **radiation.** When a body not in contact with conducting bodies cools, it is said to

radiate heat, or to cool by radiation. If a screen, such as a book, is placed between a lighted lamp and one's face, the heat is no longer felt. So we think that heat rays, like light rays, travel in straight lines. Experiments also show that heat rays, like light rays, can be reflected by a mirror, or brought to a focus by a burning glass.

Some substances, such as glass and air, let the sun's heat rays pass through almost unimpeded and are warmed but little by this radiant heat; that is, they are "**transparent-to-heat.**" Other substances, such as water, do not let heat pass through and are warmed by any radiant heat rays that strike them; they are "**opaque-to-heat.**"

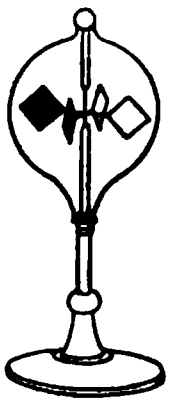

Fig. 222. Radiometer for detecting radiant energy.

191. Reflection and absorption of radiant heat. We may detect radiant heat, or energy, by means of the radiometer (Fig. 222). The glass bulb incloses four vanes which are coated with lampblack on one side and are bright on the other. These are fastened to a vertical axis so as to rotate very easily. The air has been nearly exhausted from the bulb. When radiant heat strikes the vanes, they revolve in such a direction that the blackened surface is always retreating. The velocity of rotation depends roughly on the energy received.

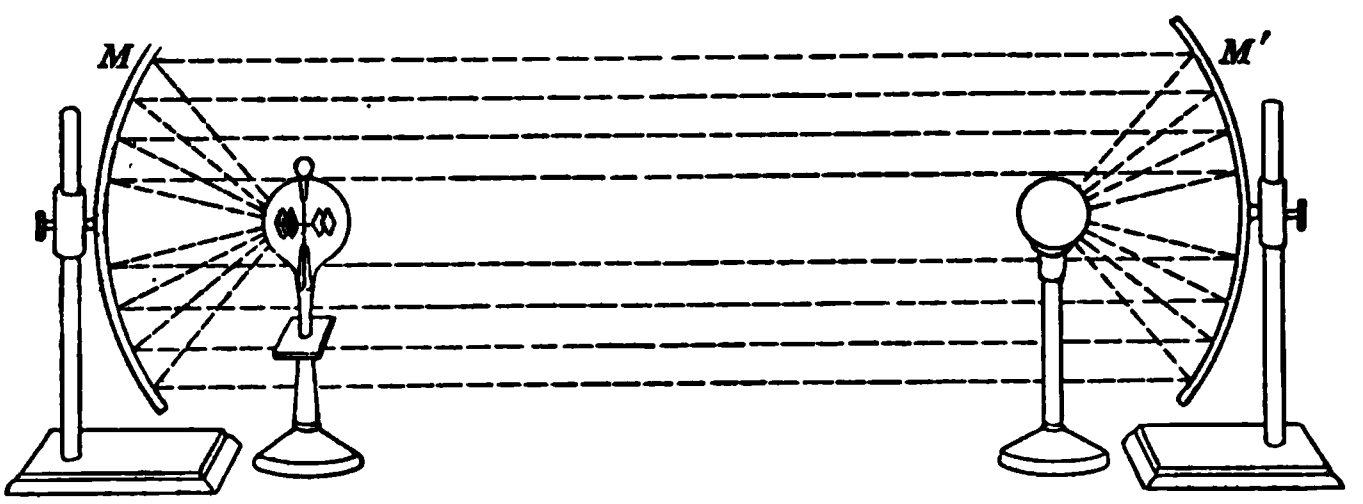

Fig. 223. Radiant energy reflected by concave mirrors.

We may show the reflection of radiant energy by placing two concave mirrors as in figure 223. The iron ball is heated almost to redness, and placed so far from the radiometer that there is no rotation due to direct radiation. Then the mirrors are set so that the ball and radiom-

eter are in the foci of their respective mirrors. Now the vanes rotate briskly because of the reflected energy.

A mirror, or any highly polished surface, is a good heat reflector, and yet itself remains cold. Fresh snow melts slowly in the sun's rays, but snow covered with soot or black dirt absorbs radiant heat and melts rapidly. *In general, reflecting or white objects do not easily absorb radiant heat, while rough or black objects absorb radiant heat readily.*

It has also been found that reflecting and bright-colored objects, when hot, cool by radiation more slowly than rough and dark objects. For example, a brightly polished silver cup radiates heat twenty times more slowly than a sooty black cup. *In general, good absorbers are good radiators, and poor absorbers are poor radiators.*

Very sensitive thermoelectric detectors of radiant heat have recently been developed to such a degree of perfection as to respond to the radiation from a single candle a mile away. They have been used to measure the heat radiated by a single star in the sky; to locate hostile bombing airplanes at night by detecting and getting the direction of the heat radiated by their engines; and even to give warning of trench raids by responding to the heat radiated by the bodies of approaching soldiers.

QUESTIONS

1. Explain how flooding a cranberry bog helps to protect the berries from frost.

2. Give two reasons for putting ashes on icy sidewalks.

3. How does the glass in a hot-house act as a trap to catch heat?

4. Why does an aviator encounter intense cold at high altitudes although his flight has brought him nearer to the sun?

5. Which is warmer, an observer on a mountain top, or one in an airplane at the same level, but over a low-lying plain?

6. Does woolen clothing supply any heat to maintain the body's temperature?

7. Why do people prefer to wear white clothes in summer and in hot countries?

8. Why should the surface of a teakettle be brightly polished and the bottom blackened?

9. Is it advisable to put any sort of aluminum or gold paint on a radiator that is to heat a room?

10. What does one mean by speaking of the cold getting into a house?

11. What would be the advantage in nickel-plating a kitchen stove instead of giving it a black finish? What would be the disadvantage?

192. Theory as to what heat is. There are many reasons for thinking that heat is a rapid vibratory motion of the molecules of substances or of the ether which fills the spaces between the molecules. We imagine that the molecules in a hot flatiron are vibrating more rapidly than when it is cold, and that this molecular vibration extends to the surrounding ether and so is sent out in straight lines in all directions as radiant heat.

At a temperature of about 550° C. iron becomes "red hot," and at 1300° C. it gets "white hot." We imagine that the iron, before it begins to glow, is sending out dark heat rays; but that, when red hot or white hot, it is sending out visible heat rays, that is, light rays. We think that these heat rays and light rays differ only in the rapidity of the vibratory motion, and in their effect on the eye. If the vibrations are under 400 trillion per second, we recognize them as *heat;* but if the vibrations are between 400 and 800 trillion per second, the nerves of the eye recognize them as *light.* Heat and light are both forms of radiant energy. This radiant energy travels at the enormous speed of 187,000 miles per second, which means that radiant energy could circle the earth seven times in one second.

On this theory, the expansion of bodies when heated is due to the more violent vibration of their molecules, which require more room to move about in. At a certain temperature this motion becomes so violent that the molecules break away from their former position and the body changes its state; that is, it melts or boils. At absolute zero this molecular motion becomes nil.

SUMMARY OF PRINCIPLES IN CHAPTER X

100 Centigrade degrees = 180 Fahrenheit degrees.

$$\text{Temp. Cent.} = \tfrac{5}{9}(\text{Temp. Fahr.} - 32).$$

Coefficient of linear expansion

$$= \text{expansion per degree for unit length}$$

$$= \frac{\text{expansion}}{\text{length} \times \text{rise in temperature}}.$$

Expansion = coefficient × length × rise in temperature.

Coefficient of volume expansion

$$= \text{expansion per degree for unit volume}$$

$$= \frac{\text{expansion}}{\text{volume} \times \text{rise in temperature}}.$$

Expansion = coefficient × volume × rise in temperature.

For solids, volume coefficient = 3 × linear coefficient.

$$\text{Pressure coefficient of gases} = \frac{\text{pressure rise}}{\text{pressure} \times \text{temperature rise}}.$$

Pressure rise = coefficient × pressure × temperature rise.

Volume coefficient of all gases nearly the same.
Pressure coefficient of all gases nearly the same. } **Value $\frac{1}{273}$.**
Volume and pressure coefficients nearly equal.

Gas law: $\frac{PV}{T} = \frac{P'V'}{T'}$.

Heat is transmitted by *convection*, *conduction*, and *radiation*.

Liquids and gases carry heat by the motion of the heated particles away from the source of heat. A *convection* current is the result of expansion.

Liquids and gases are in general poor *conductors*.

***Radiation* is the process of transmitting energy by means of *ether* waves. The sun is the great source of radiant energy. Rough, black bodies are the best radiators and absorbers.**

QUESTIONS

1. Is friction ever a source of useful heat?

2. Are the sun's rays ever used practically as a direct source of heat for engines?

3. Why does spring water seem warm in winter and cool in summer?

4. Why does the water seem much colder before a bath than afterwards?

Fig. 224. Wire handle on stove lifter.

5. Why can a platinum wire be sealed or melted into glass while a copper wire cannot?

6. Why do glass bottles crack when placed on a hot stove?

7. Why does a spiral wire handle on a poker or lifter (Fig. 224) protect the hand so much more than a solid metal handle of similar shape?

8. Why is a fur coat warmer if the fur is on the inside than if the fur is on the outside?

9. Is there any other reason than convenience for putting furnaces in cellars rather than in attics?

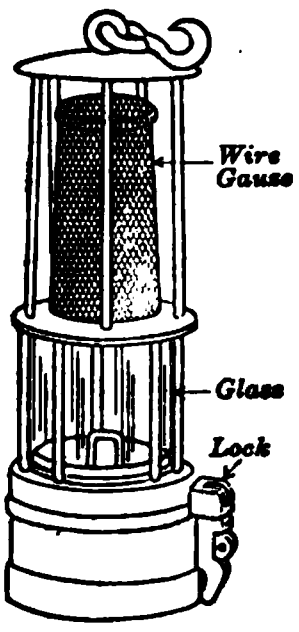

Fig. 225. Davy's safety lamp.

10. What keeps the water in the hot-water pipes in a house hot?

11. Does a hot body cool more rapidly if placed on metal than if placed on wood? Why?

12. Why does a glowing coal die out quickly on a metal shovel, and yet glow for a long time in ashes?

13. Look up Davy's lamp (Fig. 225) for miners in an encyclopedia. What is its advantage? Why is it that a flame will not strike through the fine-mesh wire gauze?

14. Why are the walls of ice houses often packed with sawdust?

15. Why should an air space be left in building the walls of brick and cement houses?

PRACTICAL EXERCISE

The use of dampers. Describe carefully with the aid of a diagram all the " dampers " of some stove or furnace you have seen, and explain how they accomplish the desired results.

CHAPTER XI

WATER, ICE, AND STEAM

Measurement of heat — B.t.u. and calorie — specific heat — freezing point — change of volume in freezing — heat of fusion of ice — boiling point under various pressures — distillation — heat of vaporization of water — steam heating — humidity — fog, rain, and snow — ice-making.

193. How we measure heat. If a man buys a ton of coal, what does he get for his money? One answer would be, about 2000 pounds of material, of which, perhaps, 60 pounds is water, 240 pounds is ash, and the rest mostly carbon and hydrogen. What the man is really interested in, however, is not the sort of material, but the amount of heat he has bought. Since heat is not a substance, but a form of energy, we cannot measure it directly in pounds or quarts, but must measure it by the effect it can produce. For example, if one pound of hard coal could be completely burned, and if all the heat generated in this process could be used to heat water, it would be found that about 7 tons of water could be raised 1° F. in temperature. Engineers reckon the heat value of fuel in units such that each represents the *heat required to raise one pound of water one degree Fahrenheit.* This heat unit is called the "**British thermal unit,**" and is written B.t.u.

Some average heat values are:

Illuminating gas	600 B.t.u. per cu. ft.
Dry wood	5000 B.t.u. per pound
Dry coal	14,000 B.t.u. per pound
Kerosene or gasoline	19,000 B.t.u. per pound

The heat unit employed in Europe, and in all physical and chemical laboratories, is a metric unit called the **gram calorie.**

The gram calorie is the heat required to raise the temperature of a gram of water one degree centigrade.

194. Heat absorbed by different substances. It is well known that a kettle of water on a stove gets warm much less quickly than a flatiron of the same *weight*. The heat which is required to warm a kilogram of water 1 degree will warm the same *weight* of aluminum about 5 degrees, of zinc or copper about 10 degrees, of silver or tin about 20 degrees, and of lead or mercury about 30 degrees. In fact, experiments show that water requires more heat per unit weight per degree rise of temperature than any other common substance.

Since one calorie is required to raise the temperature of one gram of water 1 degree, only one tenth of a calorie would be needed to raise the temperature of one gram of copper a degree, one twentieth of a calorie to raise a gram of silver 1 degree, and one thirtieth of a calorie to raise a gram of lead 1 degree. *The number of calories required to raise the temperature of a gram of a substance one degree centigrade is called its* ***specific heat.*** Thus the specific heat of water is 1, of copper about 0.1, etc. In the English system the specific heat of a substance is *the number of B.t.u. required to raise the temperature of a pound of the substance one degree Fahrenheit.* Notice that the numerical value of a specific heat is the same in both systems. Why?

The following experiment illustrates how much substances differ in their specific heats.

We may heat a number of cylinders of the same weight but of different metals, such as iron, copper, tin, and lead, to about 150° C. in oil. Then if we place them all at the same time on a thin cake of paraffin wax, as shown in figure 226, they will melt the wax and sink into it, but to different depths. The iron sinks farthest, the copper and tin come next, while the lead makes but little headway. The metal with the largest specific heat gives out the largest amount of heat in cooling, and so melts the most paraffin.

Fig. 226. Metals differ in specific heat. Iron has greater specific heat than lead.

195. How specific heat is determined. When a hot substance, such as hot mercury, is poured into cold water, the water and mercury soon come to the same temperature. The heat given up by the cooling mercury is used in warming the water. If no heat is lost in the process, *the heat units given out by the hot body are equal to the heat units gained by the cold body.*

This **method of mixtures** is accurate only when no heat is lost during the transfer. This is rather difficult to manage in practice. Nevertheless, the method is the one generally used in laboratories to determine the specific heats of substances.

FOR EXAMPLE, suppose that 300 grams of mercury are heated to 100° C. and then quickly poured into 100 grams of water at 10° C., and that, after stirring, the temperature of the water and mercury is 18.2° C.

If we let x be the specific heat of the mercury, the mercury gives out $300(100 - 18.2)x$ calories. Since the specific heat of water is 1, the water absorbs $100(18.2 - 10)1$ calories. Therefore we may make the equation

$$\textit{Heat given out} = \textit{Heat taken in.}$$
$$300(100 - 18.2)x = 100(18.2 - 10)1$$
$$\text{whence} \qquad x = 0.033 \text{ calories.}$$

By very careful experiments of this sort the specific heats of some of the common substances have been found to be as follows:

TABLE OF SPECIFIC HEATS

(Either metric or English units)

Water	1.00	Zinc	0.094
Ice	0.50	Copper	0.093
Air	0.24	Silver	0.056
Aluminum	0.22	Tin	0.055
Dry soil	0.20	Mercury	0.033
Iron	0.11	Lead	0.031

It is remarkable that of all ordinary substances water has the greatest specific heat. Thus it takes about five times as much heat to raise a pound of water 1 degree as to raise a pound of solid earth 1 degree, and so the ocean acts as a great

moderator of temperatures. In summer the water absorbs a vast amount of heat, which it gives up slowly in winter to the land and air. This explains why the temperature on some ocean islands does not vary more than 10° F. during the whole year.

PROBLEMS

1. How many calories of heat are needed to raise the temperature of 10 grams of water 5° C.?

2. How many calories are required to heat 15 grams of iron 20° C.?

3. Compute the calories given out by a kilogram of copper in cooling from 110° C. to 15° C.

4. How many B.t.u. are necessary to heat a 2-pound flatiron from 70° F. to 350° F.?

5. From the definition of the two units of heat, compute the number of calories which are equivalent to 1 B.t.u.

6. How many tons of water can be heated from 32° to 212° F. by the combustion of 1 ton of coal, in a boiler whose efficiency is 75%?

7. If coal costs $5.00 per ton and gas costs $1.00 per 1000 cubic feet, how much heat (B.t.u.) can be secured for 1 cent's worth of each?

8. How much does it cost to heat 30 gallons of water from 50° F. to 200° F. with a gas heater whose thermal efficiency is 75%?

9. If 400 grams of water at 100° C. are mixed with 100 grams of water at 20° C., what will be the temperature of the mixture?

10. It is desirable to prepare a bath containing 20 gallons of water at 40° C. If the supply of hot water is at 60° C. and that of cold water at 10° C., how much of each would you use?

11. If 500 grams of copper at 100° C., when plunged into 300 grams of water at 10° C., raise the temperature to 22° C., what is the specific heat of copper?

12. A piece of iron weighing 150 grams is warmed 1° C. How many grams of water could be warmed 1° by the same amount of heat? (The answer is called the **water equivalent** of the piece of iron.)

13. A 50-pound iron ball is to be cooled from 1000° F. to 80° F. by putting it in a tank of water at 32° F. How many pounds of water must there be in the tank?

14. A platinum ball weighing 100 grams is heated in a furnace for some time, and then dropped into 400 grams of water at 0° C., which is raised to 10° C. How hot was the furnace? (Sp. heat = 0.04.)

15. A copper kettle weighing 1000 grams contains 2000 grams of water at 10° C. Heat is supplied by a gas flame which furnishes 15,000 calories per minute. How long a time will be required to raise the water to 100° C.?

16. When a hot-air furnace is driven on a cold day, each register may discharge 15 pounds of air per minute. Suppose there are 8 such registers, and the furnace has an efficiency of 60%. If all this air is taken in from out of doors where the average temperature is 20° F. and heated to 80° F., how much coal is required per week?

17. Under the conditions of the last problem, how much coal is saved per week if four fifths of the air that circulates through the furnace is taken from the house at an average temperature of 70°, and only one fifth from out of doors?

Practical Exercise

Heat value of coal. If a Parr bomb calorimeter is available, the heat value (B.t.u. per pound) of a sample of coal may be readily determined. The results are accurate to about 1%. Full directions for the manipulation and calculation are furnished with the instrument.

196. Melting and freezing. If a pailful of snow or ice is brought in from out of doors on a cold winter day and set on a stove, one finds that its temperature is at first below 0° C. and slowly rises to that point. It then remains stationary, or nearly so, until all the snow is melted. Then the temperature of the water gradually rises. This stationary temperature, where the ice (snow) changes to water, is called the **melting point** of ice, and is 0° C., or 32° F.

We may also determine the freezing point of water by making a freezing mixture of cracked ice and salt and placing it in a test tube containing some pure water. The temperature of the water will be observed to fall slowly until the water begins to freeze. Then the temperature remains constant until all the water is frozen. This stationary temperature at which water changes into ice is called the **freezing point** of water, and is 0° C., or 32° F.

Substances which are crystalline, such as ice and many metals, change into liquids at a definite temperature, and the melting

point of such a substance is the same as its freezing point. Non-crystalline substances, such as iron, glass, and paraffin, pass through a soft, pasty stage as the melting point is approached. In the case of some substances, such as the fats, the melting point is not the same as the freezing point. Thus butter will melt between 28° and 33° C. and yet solidifies between 20° and 23° C.

TABLE OF MELTING OR FREEZING POINTS

Tungsten	3000° C.	Lead	327° C.
Platinum	1755° C.	Tin	232° C.
Steel	1300 to 1400° C.	Sulfur	115° C.
Glass	1000 to 1400° C.	Naphthalene (moth balls)	80° C.
Cast iron	1100 to 1200° C.	Paraffin	about 54° C.
Copper	1083° C.	Ice	0° C.
Gold	1063° C.	Mercury	−39° C.
Silver	960° C.	Alcohol	about −112° C.

There are several alloys of metals which melt at a much lower temperature than any of the metals of which they are made. "Wood's metal" (2 tin + 4 lead + 7 bismuth + 1 cadmium by weight) melts at 70° C., although the lowest melting point of any of its constituents, tin, is 232° C. Wood's metal will melt even in hot water. Such alloys are used to seal tin cans and automatic fire sprinklers.

197. Expansion in freezing. In general, when a liquid freezes, it contracts, because the molecules are more closely knit together in the solid than in the liquid state. But when we recall that ice floats and pitchers of water are often cracked by freezing, we see that water expands on freezing. In fact, a cubic foot of water becomes 1.09 cubic feet of ice. Cast iron is another substance that expands a little in solidifying. It is therefore adapted to making castings, for in this way every detail of the mold is sharply reproduced. Of course allowance has to be made for shrinkage in cooling. In making good type a metal is needed which expands a little on solidifying; and so an alloy of lead, antimony, and copper, which has this property, is used.

That the expansive force of water in freezing is enormous can be seen from the following experiment.

Let us fill a cast-iron bomb with water, close the hole with a screw plug (Fig. 227), and put the bomb in a pail of ice and salt. When the water in the bomb freezes, the pressure inside increases more and more, and the bomb eventually explodes.

Fig. 227. Expansive force exerted by freezing water breaks the iron bomb.

This shows why water pipes and automobile radiators burst on nights cold enough to freeze the water in them. A similar process is active every winter in breaking the rocks of mountains to pieces. Water percolates into the crevices, freezes, and expands.

198. Effect of pressure on melting ice. If we suspend a weight of 40 or 50 pounds by a wire loop over a block of ice (Fig. 228), the wire will cut slowly through the ice. The pressure causes the ice to melt under the wire; but the water flowing around the wire freezes again above, and leaves the block as solid as before.

This experiment shows that pressure causes ice to melt by lowering the freezing point. This might be expected, for pressure on any body tends to prevent its expansion, and since water expands on freezing, pressure tends to prevent freezing; that is, it lowers the freezing point. It requires, however, a pressure of almost a ton (1850 pounds) per square inch to lower the freezing point 1 degree centigrade.

Fig. 228. Wire cutting through a block of ice.

In skating, the high pressure under the edge of the skate blade melts the ice and forms a film of water which is very slippery. This also explains how snowballs can be made by pressing the snow between the hands. The pressure at the points of contact between the flakes of snow melts them and then the

film of water that is formed freezes again when the pressure is released. The flow of glaciers of solid ice around corners is explained in the same way.

199. Heat required to melt ice. If a dish of ice and water at 0° C. is kept in a room where everything else is at 0°, the ice will not melt and the water will not freeze. But if the dish is surrounded by a freezing mixture, such as salt and ice, the water will freeze, or if the dish is brought into a warm room, the ice will melt. In either case, however, the *temperature* of the mixture will remain steadily at 0° until either all the ice is melted or all the water is frozen.

It seems evident, then, that when ice melts, heat energy is absorbed, which does not show itself in a rise of temperature. This is called the **heat of fusion of ice**, or the latent (or hidden) heat of melting ice.

200. How much heat to melt 1 gram of ice? In solving this problem we may apply the method of mixtures which was used in determining the specific heat of a metal.

FOR EXAMPLE, if we put 200 grams of ice at 0° C. into 300 grams of water at 70° C. and stir them thoroughly, the temperature of the water, after the ice is all melted, will be 10° C.

Let x = no. of calories required to melt 1 g. of ice.
Then $200\,x$ = no. of calories required to melt 200 g. of ice.
Also 200×10 = no. of calories required to raise melted ice from 0° to 10°
and $300(70 - 10)$ = no. of calories given out by the water in cooling.

Heat units taken in = Heat units given out.

Then $200\,x + 200 \times 10 = 300\,(70 - 10)$
whence $x = 80$ calories.

The best experiments that have been made show that the *heat of fusion of ice is just about* ***80 calories***, which means that 80 calories are absorbed in changing 1 gram of ice at 0° C. into water at 0° C.

201. Heat given out when water freezes. We have just seen that heat energy is required to pull apart the molecules of the solid ice and change it into the liquid state, where the

molecules are held together less intimately. Now we wish to show that in the reverse process, that is, in freezing, this energy appears again as heat. We may show that freezing is a heat-evolving process in the following experiment.

If we repeat the experiment described in section 196, except that we keep the water, thermometer, and test tube (Fig. 229) very quiet, we shall be surprised to find that the water will cool several degrees below 0° C. before the freezing begins. When once started by stirring or dropping in an ice crystal, freezing goes on rapidly; but the temperature jumps to 0° C. and remains stationary until all the water is frozen. The latent heat given out in freezing is absorbed by the colder freezing mixture in the jar outside.

People sometimes make use of the heat given out by water when it freezes, by putting pails or tubs of water in a greenhouse or a cellar to prevent the freezing of the plants or vegetables. As the water begins to freeze first, the heat evolved in the process prevents the temperature from falling much below 0° C. When a large lake freezes, the heat evolved helps to keep the temperature in its vicinity from falling as low as it does farther away.

Fig. 229. Freezing water evolves heat.

202. How melting ice is used in a refrigerator. We all know that a refrigerator is merely a box with ice in the top (Fig. 230) which is used to keep food cool. The air around the ice is cooled, settles down on account of its greater density, takes up heat from the food or from the walls, and rises again, as indicated by the arrows. The cooling of the air is due almost entirely to the absorption of heat by the ice in melting. Therefore, a refrigerator in which ice did not melt at all (if there were such a one) would be quite useless. Furthermore, while a fabric cover for the ice may be a good means of saving ice, it is a poor way to save food. On the other hand, it is not economical to let ice melt in a refrigerator merely because heat leaks in through the walls. The two essentials in economical refrigeration are, first, that the transfer of heat from the food to the ice should be furthered in

every way possible; and second, that the transfer of heat from the room to the ice should be hindered in every way possible. The first requires free and unimpeded convection currents inside; the second requires that the walls should be very well insulated, and that the doors should be tight and should never be left open longer than is absolutely necessary.

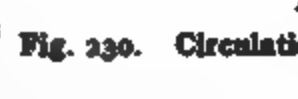

Fig. 230. Circulation of air in refrigerator.

Questions and Problems

1. How many calories of heat are required to melt 20 grams of ice at 0° C.?

2. How much heat is evolved in cooling and freezing 12 grams of water originally at 10° C.?

3. How much water at 100° C. will be needed to melt 300 grams of snow at 0° C., and raise its temperature to 20° C.?

4. How many grams of ice must be put into 300 grams of water at 35° C. to lower the temperature to 10° C.?

5. If a 500-gram iron weight is heated to 250° C. and placed on a block of ice, how many grams of the ice will be melted?

6. How many times as much heat is required to melt any quantity of ice as to warm the same quantity of water 1° C.? To warm the same quantity of water 1° F.? How many B.t.u. are required to melt 1 pound of ice?

7. In testing two refrigerators the following results were obtained:

	Room temperature	Coldest inside temperature	Weight of ice melted per hour
No. 1	92.1° F.	52.7°	1.50 lb.
No. 2	91.8° F.	57.2°	1.78 lb.

Which would you consider the better refrigerator and why?

8. If the price of ice is 50 cents per hundred pounds and the price of gas is $1.00 per thousand cubic feet, which is more expensive, to *absorb* or to *produce* heat?

Practical Exercise

Testing a refrigerator. In Circular No. 55 of the Bureau of Standards, entitled *Measurements for the Household*, on page 53 are given the results of tests of nine refrigerators. Try to make as complete a test as possible of the refrigerator in your own home.

203. Process of boiling water. Let us fill a round-bottomed flask (Fig. 231) half full of water and put through the stopper a thermometer, an open manometer, and an outlet tube for the steam. At first, as the water is heated, the air which is dissolved in the water rises to the surface in little bubbles. Then bubbles of steam form at the bottom; but these collapse when they strike the upper, cooler layers of water, and disappear, causing the rattling noise known as "singing" or "simmering." When the bubbles of steam begin to reach the surface, the water is said to "boil." It will be noticed that the steam in the flask is as clear as air, but as it leaves the outlet tube it condenses and forms a white cloud or mist.

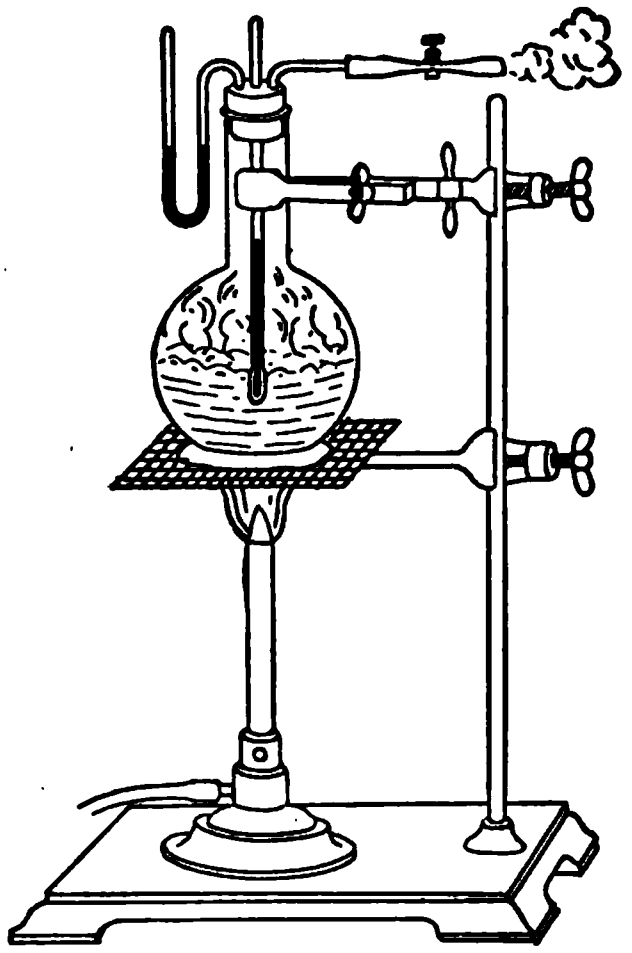

Fig. 231. Boiling water in a flask.

As soon as boiling begins, the thermometer, which has been rising rapidly, reaches 100° C. and remains stationary.

If we partly close the outlet valve, the manometer shows an increase of pressure, and the thermometer shows a corresponding rise in the temperature of the boiling water.

Finally, we remove the burner, let the water cool a bit, and then connect the outlet tube with an aspirator, which reduces the pressure and makes the water boil again.

The process of boiling consists in the formation in a liquid of bubbles of vapor, which rise to the surface and escape. The temperature at which this takes place is the *boiling point* of the liquid.

There is a second and more exact definition of the boiling point. It is evident that a bubble of water vapor can exist

within the liquid only when the pressure exerted outward by the vapor within the bubble is at least equal to the atmospheric pressure pushing down on the surface of the liquid. For if the pressure within the bubble were less than the outside pressure, the bubble would immediately collapse. Now the pressure that would exist inside a bubble, if it could form at all, would be different at different temperatures. It is called the **vapor pressure**, or **vapor tension**, of the liquid, and we shall soon see how to determine its values at different temperatures. *The **boiling point** of a liquid may therefore be defined as the temperature at which its vapor pressure is one atmosphere.*

204. Effect of changing pressure. The following interesting experiment shows water boiling under reduced pressure.

Let a flask, half-full of water which is boiling vigorously, be removed from the flame and instantly corked air-tight with a rubber stopper. We may then invert the flask, as shown in figure 232, and cool the top by pouring on cold water. The water in the flask immediately begins to boil again. This is because the steam in the top of the flask is condensed and so the pressure on the surface of the liquid is much reduced.

Fig. 232. Boiling water under a faucet.

The last two experiments have shown that if the pressure on the surface of the liquid is increased, the temperature has to be raised before the liquid will boil, while if the pressure is decreased, the liquid will boil at a lower temperature. We can understand this if we recall that ordinarily the atmosphere is exerting a pressure of about 15 pounds per square inch on the surface of the liquid. If we reduce this pressure, it is easier for the bubbles of vapor to form; if the pressure is increased, it is more difficult for the bubbles to form. In any

case, they will form only when the temperature is high enough so that, when they have formed, the pressure in them is equal to the pressure on the surface of the liquid. So, by observing the temperatures at which a liquid boils under different pressures, we can determine how the vapor pressure of the liquid changes with temperature. Experiments have shown that, near 100° C., *the vapor pressure of water increases by about 27 millimeters of mercury for each centigrade degree rise of temperature.*

The following table shows how the temperature of boiling water changes with the pressure both below and above atmospheric pressure.

TEMPERATURE OF WATER BOILING AT VARIOUS PRESSURES

Absolute pressure Lbs. / sq. in.	Fahrenheit temperature	Centigrade temperature	Absolute pressure Lbs. / sq. in.	Fahrenheit temperature	Centigrade temperature
1	102°	39°	20	228°	109°
3	142°	61°	25	240°	116°
6	170°	77°	30	250°	121°
10	193°	90°	40	267°	131°
14.7	**212°**	**100°**	50	281°	138°

Since we have defined the 100° point on the centigrade scale as the temperature of boiling water, and since the temperature at which water boils is so much affected by changes in pressure, it is necessary to fix on some **standard pressure** at which thermometers are to be "calibrated," or marked. By common agreement, this standard pressure is the pressure exerted by a column of mercury 760 millimeters high, the temperature of the mercury being 0° C. The temperature at which water boils under this pressure is, by definition, 100° C.

205. Applications. Sometimes it is very desirable to boil liquids at as low a temperature as possible. For example, the water is boiled away from sirup and from milk in what are called **vacuum pans**, which are merely closed kettles with part of the air pumped out. The water boils away at about 70° C. and leaves the granulated sugar or milk condensed, but not cooked.

On the tops of high mountains the temperature of boiling water is so low that eggs cannot be cooked. In Cripple Creek, Col., about

10,000 feet above sea level, it takes about twice as long to cook potatoes as in Boston. At these high altitudes closed vessels provided with safety valves, called "digesters" or "pressure cookers" (Fig. 233), have to be used in cooking. Such kettles are also needed for hastening the cooking of certain foods and for the rapid sterilization of products that are to be canned. Digesters are commercially used for extracting gelatin from bones. The effect of the increased pressure in a digester, or pressure cooker, is the same as in a boiler. The water in a boiler whose gauge reads 100 pounds is boiling, not at 100° C., but at 170° C., or 338° F.

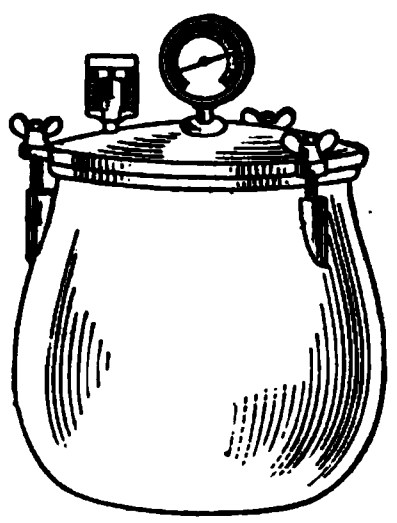

Fig. 233. Pressure cooker for domestic use.

206. Summary. What has been said about the process of boiling can be summarized as follows:

(1) *A liquid will boil only when its temperature is such that its vapor pressure is equal to the pressure on its surface.*

(2) *What is called "the boiling point" of a liquid is the temperature at which it will boil under atmospheric pressure; that is, the temperature at which its vapor pressure is one atmosphere, or 760 millimeters of mercury.*

(3) *Every liquid has its own boiling point. The boiling point of water is by definition 100° C.*

(4) *The rule about boiling under other pressures than one atmosphere is, the higher the pressure, the higher the temperature required to make the liquid boil.*

TABLE OF BOILING POINTS

(At a pressure of 760 millimeters)

Zinc	918° C.	Alcohol	78° C.
Sulfur	445° C.	Ether	35° C.
Mercury	357° C.	Ammonia	− 34° C.
Saturated salt solution	108° C.	Oxygen	− 183° C.
Water	100° C.	Hydrogen	− 253° C.

207. Distillation. In many localities the only way to be sure of getting pure water is by what is called distillation.

The water is boiled in a vessel which is so arranged that the steam will pass through a cold tube and again return to the liquid condition (Fig. 234). This change of water vapor to liquid water is called condensation, and the apparatus in which it takes place is called a condenser. The water which drops from the end of the condenser is pure, the impurities being left behind in the vessel in which the water was boiled.

Fig. 234. Purification of water by distillation.

The process of distillation consists of boiling a liquid and condensing its vapor. In commercial work this is usually done in a "worm condenser." This consists of a pipe coiled into a spiral and surrounded by circulating cold water (Fig. 235). In this way a large condensing surface is obtained in a small space.

When a mixture of two liquids is distilled, the vapor formed contains much more of the substance with the lower boiling point than did the original mixture. This substance can thus be more or less completely separated from the one with the higher boiling point. It is by this process of **fractional distillation** that gasoline and kerosene are obtained from crude petroleum. Gasoline distills over between 70° and 120° C. and kerosene between 150° and 300° C.

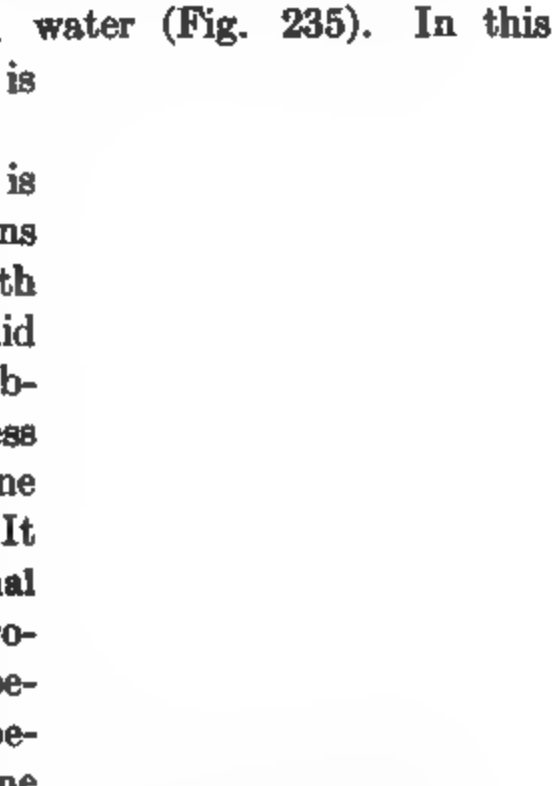

Fig. 235. Worm condenser offers a large cooling surface.

Questions and Problems

1. How is the temperature of boiling water affected by taking the water to the bottom of a deep mine?

2. If water boils at 99° C., what is the atmospheric pressure?

3. If water boils at 208° F., what does the barometer read?

4. An elevation of 900 feet makes a difference of about 1 inch in the barometer. At what temperature would water boil 1500 feet above the sea?

5. In Altman, Colorado, which is one of the highest towns in the country, the temperature of boiling water is about 88.5° C. What is the altitude (approximately)?

6. Plot a vapor-pressure curve for water, laying off temperatures horizontally and pressures vertically. (Hint: Use 5 small divisions for 10° F., or 10 small divisions for 10° C., and use 20 small divisions for 10 pounds per square inch.)

7. A certain pressure cooker is designed to cook at 20 pounds of steam pressure above atmospheric pressure. What is the temperature inside?

8. What effect does salt or sugar have on the boiling point of water? Try it.

9. What effect does a little denatured alcohol have on the boiling point of water? Try it. What bearing does this have on the use of alcohol in automobile radiators in winter?

10. In distilling petroleum, some of the products are petroleum ether, gasoline, naphtha, and kerosene. Which distills over first?

11. Mark Twain in his "Tramp Abroad" tells of stopping on his way up a mountain to "boil his thermometer." What did he do, and why?

208. Heat of vaporization of water. When a kettle of water is put on a stove, it gets hotter and hotter until it boils. Then, no matter how much heat we apply to the kettle, if there is a free outlet for the steam to escape, the temperature remains constant at 100° C., or 212° F. The heat energy which seems to disappear in boiling the water is called the **heat of vaporization** or the latent heat of steam. This heat of vaporization is the energy needed to pull the molecules of water away from each other and set them free as steam.

209. How much heat is needed to make a gram of steam? When we want to determine the amount of heat needed to change a gram of water at 100° C. into steam at 100° C., we use the method of mixtures, and instead of measuring the heat absorbed in making steam, we measure the heat given off when steam condenses.

FOR EXAMPLE, suppose we take 400 grams of water at 5° C. and run in enough dry steam at 100° C. to raise the temperature of the water to 35° C. We then find by weighing that we have 420 grams of water, showing that 20 grams of steam were condensed. How many calories of heat are given out by 1 gram of steam in condensing to water at 100° C.?

Let x = heat of vaporization.
Then $400(35 - 5)$ = heat absorbed by cold water,
$20\,x$ = heat given out by condensing of steam,
and $20(100 - 35)$ = heat given out by resulting water in cooling from 100° to 35° C.

Heat units absorbed = Heat units given out,
then $400(35 - 5) = 20\,x + 20(100 - 35)$
and $x = 535$ calories.

Recent experiments have shown that the *heat of vaporization of water is about 540 calories.* In other words, it takes more than five times as much heat to change any quantity of water into steam as to raise the same quantity of water from the freezing to the boiling point. In English units it requires 540 × 1.8, or 972 B.t.u. to change a pound of water at 212° F. into steam at 212° F.

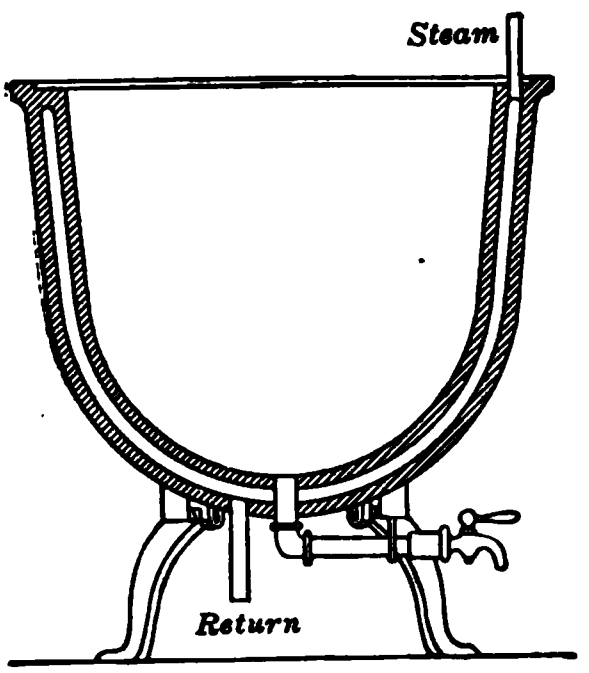

Fig. 236. Steam-heated soup kettle.

210. Steam heating. The fact that the heat of vaporization of water is so much larger than the heat it gives out while cooling through any practical temperature range shows why

steam is so much used for heating. Steam is formed in a boiler, each pound of water absorbing something like 1000 B.t.u. as it is warmed and vaporized. The steam is piped to the place where heat is desired and is then condensed, giving out the 1000 B.t.u. again. The hot water formed by the condensation then runs back into the boiler by gravity. The pressure in such a system is commonly only a few pounds above atmospheric.

In the kitchens of hotels and large restaurants, soups and chowders are made and vegetables are boiled in great double-walled copper

Fig. 237. Diagram of indirect heating system.

kettles (Fig. 236), the contents of which are heated by admitting steam to the space between the walls. In sugar refineries the sirup is boiled down by condensing steam in coils immersed in vats of the liquid. In both cases the temperature at which the process is carried on can be controlled and held constant, as closely as may be desired, by passing the incoming steam through a reducing valve that admits fresh steam just fast enough to keep the pressure of the condensing steam constant.

Factories, office buildings, hotels, schoolhouses, and other large buildings are usually heated by steam which is formed in one or more boilers in the basement. Sometimes the steam is condensed in radiators in the various rooms; more often it is condensed in coils or grids

of pipe over which fresh air is drawn, thus providing for ventilation as well as heating. Such a system is called **indirect heating** (Fig. 237). When radiators are used, they are likely to become air-bound; air gets into the system when it is not in use, or is introduced in solution in the water fed to the boiler and tends to collect in the radiators. Then it quickly cools off and prevents steam from entering. This difficulty is overcome automatically by a small air vent on each radiator. In one type of vent (Fig. 238) there is an ebonite rod *A* which, when cool, is short enough to leave the hole at the top open so that the entrapped air can escape. When hot steam reaches the ebonite, it lengthens and closes the valve. If water reaches the vent, the bell *B*, which always contains some air, floats and closes the valve.

Fig. 238. Automatic radiator vent.

As a means of heating dwellings, the system described above is inconvenient, because the temperature of steam condensing at atmospheric pressure is 212° F., and this makes the radiators much too hot in mild weather. This difficulty is overcome in the so-called "vapor" systems by purposely letting the radiators stay air-bound, only enough air being bled off to keep a suitable part of each radiator active. In such systems the radiators have no air vents, but at the outlet from each radiator there is a valve which passes either air or condensed water, but not steam. A valve like figure 238 would do this if the bell were left out; another type is shown in figure 239. This type contains an air-tight copper box with corrugated sides. When this box is made, a bit of blotting paper soaked in gasoline is put inside and the box is then sealed up. When the box is surrounded by hot steam, the vapor pressure of the gasoline inside stretches the box and this closes the valve. Either water or air is so much cooler than steam that the box contracts and the valve opens.

Fig. 239. Water and air relief trap.

In factories, the **vacuum system** of steam heating is often used. The whole system is made air-tight, and a vacuum pump is installed which pumps both air and water out through the return pipes so as to maintain a partial vacuum in the radiators. If the remaining pressure in the radiators is one third of an atmosphere, the temperature of the condensing steam is about 161° F.; and if the pressure is only one tenth of an atmosphere

the temperature is only about 115° F. In this way the heating action of the radiators can be regulated to suit the weather.

One advantage of steam heating in factories is that it can be combined with a power plant, the steam being generated at high pressure and used in a steam engine which discharges it at the pressure desired in the heating system. This plan gives both heat and power at a total cost only a little greater than that of either by itself.

PROBLEMS

1. Find the number of calories required to change 15 grams of water at 100° C. into steam.

2. How many calories are required to heat a kilogram of water from 20° C. to 100° C. and convert it into steam?

3. How many B.t.u. are needed to change 20 pounds of water at 40° F. into steam at 212° F.?

4. Compute the heat evolved by condensing 10 grams of steam at 100° C. and cooling it down to 50° C.

5. How much heat will be required to convert 1 kilogram of ice at 0° C. into steam at 100° C.?

6. How much steam at 100° C. must be run into 500 grams of water at 10° to raise it to 40°?

7. A swimming pool is 60 feet long and 30 feet wide, and the average depth of the water is 5 feet. Steam at 212° F. is run in to raise the temperature of the water from 63° F. to 68° F. How many pounds of steam are needed?

8. In the illustrative example in section 209, the heat of vaporization came out 535, which is a little too low. This shows that the steam was not dry. How much of the steam had already condensed?

9. A certain alcohol stove, designed for polar expeditions, was found to change 4 kilograms of ice at −40° C. to water at 100° C. in 10 minutes by burning 140 grams of alcohol. If the heat of combustion of denatured alcohol is 6000 calories per gram, and if the specific heat of ice is 0.5, what was the thermal efficiency of the stove?

10. How many pounds of coal will be needed in a boiler whose efficiency is 65% to convert 100 pounds of water at 50° F. into steam at 212° F.? Assume that the heat value of the coal is 14,500 B.t.u. per pound.

Practical Exercises

1. Pressure cooker. Attach a thermometer to the cover of a pressure cooker. Fill the kettle about one third full of water and heat the water till the thermometer indicates a little over 212° F. Then stop heating, open the safety valve, and let out the air. Now heat again and record the temperature for each two pounds increase of pressure up to 20 pounds per square inch. Heat slowly. Plot your results as a curve and compare with the table on page 238.

2. Steam-heating plant. Study the boilers in the heating plant of the school building, an apartment house, or a factory. What kind of fuel is used? Where does the water come from? How is the water heated? What three safety devices are attached to the boiler? Is the steam distributed through a one-pipe or a two-pipe system? How are the rooms ventilated?

211. Evaporation. Everyone is familiar with the fact that water left in an open dish gradually disappears, or evaporates. **Evaporation** is different from **boiling**, in that evaporation takes place at any temperature, but only at the surface of a liquid; while boiling goes on inside the liquid, but only at a fixed or definite temperature. Evaporation goes on more rapidly the warmer and drier the surrounding air is. For example, wet clothes dry more quickly on a hot day than on a cold, foggy day.

212. Cooling by evaporation. If one pours a few drops of alcohol or ether on one's hand, the liquid quickly evaporates, causing a marked sensation of cold. Whenever a liquid evaporates, it must get heat from somewhere, and so the *temperature of the liquid itself and of anything near it drops.* That is to say, heat is absorbed in the process of evaporation. It is always more comfortable on a hot day to ride in a car than to sit still, because the rapid circulation of the air makes the moisture of the skin evaporate more rapidly. This is why one can tell the direction of the wind by lifting a moistened finger; the wind blows from the side which feels cool.

213. Moisture in the air. In the summer time the outside of a pitcher of ice water is usually covered with drops of water.

It might at first be thought that these were due to the water oozing through pores in the side of the pitcher; but the microscope does not show any pores in glazed porcelain or glass, so we must conclude that the drops come from the surrounding air. The air is cooled by coming in contact with the cold pitcher and deposits some of its moisture. If we put a little water in a bottle and cork it tightly, the water does not evaporate because the air above the water quickly becomes "saturated" with moisture. Thus we see that air can take up only a definite quantity of moisture, depending on the temperature.

Let us place a little water in a thin-walled flask and cork it. If we place the flask in the sun or in an oven until it becomes warm, and then cool it, its walls become dim, because of the drops of water. The warm saturated air becomes "supersaturated" on cooling.

Careful experiments show that a cubic meter of **saturated air** contains at different temperatures the following amounts of water vapor:

2 grams at	−10° C.	17 grams at	20° C.
5 grams at	0° C.	30 grams at	30° C.
9 grams at	10° C.	597 grams at	100° C.

From this table it will be seen that air, which is saturated at one temperature, can, at a higher temperature, take up still more water vapor before becoming saturated; but if cooled, it must deposit some of the water vapor which it already has.

After a shampoo or a swim, a lady finds that her hair dries slowly because the air near all the wet surfaces quickly becomes almost saturated with moisture. If this layer of saturated air is continually replaced by dry air, as in a breeze or when a fan or electric blower is used, evaporation and drying proceed much more rapidly. "Electric towels" work similarly by blowing warm air on one's hands.

214. Relative humidity. Usually the air does not contain all the moisture which it can hold; that is, it is not saturated. If, however, the temperature suddenly drops, the same actual amount of moisture will saturate the air.

If the water in a polished nickel-plated cup is cooled with ice below the temperature of the room, a mist appears on the outside of the cup. The temperature of the water when this occurs is the " dew point."

The dew point is the temperature at which the water vapor in the air begins to condense. If the air is cooled below the dew point, some of its vapor condenses, and dew collects on objects. Thus we see that the words " dry " or " moist," as applied to the atmosphere, have a purely relative significance. They involve a comparison between the amount of water vapor actually present, and that which the air could hold if saturated at the same temperature. The ratio of these two quantities is called the **relative humidity**. For example, we may read in the newspaper that the relative humidity is 85%. This means that the amount of water vapor actually present in the air is 85% of what the air might have contained at the given temperature if it had been saturated.

215. Wet- and dry-bulb thermometers. Let two thermometers be arranged as shown in figure 240. The bulb of the thermometer at the left is dry, while the other thermometer has its bulb covered with a cotton wick which is kept moist by a cup of water. If we keep the air around the thermometers circulating by an electric fan, after a little while the wet-bulb thermometer will indicate a lower temperature than the dry-bulb thermometer. This cooling is caused by the evaporation of water from the cotton wick. The drier the surrounding air, the more rapid will be the evaporation, and so the greater will be the difference between the wet- and dry-bulb thermometers. By means of tables furnished with the instrument, we may determine from these thermometer readings the relative humidity of the air.

Fig. 240. Wet- and dry-bulb thermometers used to find humidity of air.

216. Practical importance of determining humidity. It is well known that a hot day in Boston is much more uncomfortable than an equally hot day in Denver. This is because a city near the ocean, like Boston, has a higher relative humidity than a city which is inland and a mile above sea level, like Denver. When the relative humidity is high, we feel "sticky," because the perspiration of the skin does not evaporate readily. On the other hand, too little humidity is injurious. Special precautions are taken to keep the air in schools, hospitals, private houses, and especially greenhouses from getting too dry in winter. In cotton mills it has been found that the air must be rather moist to make the spinning of yarn successful.

Since the occurrence of frost in the late spring or early fall is injurious to many crops, it is often highly important that farmers should know in the afternoon whether freezing weather during the night is to be expected. The temperature of the dew point gives a ready means of predicting how low the temperature at night will drop; for when the dew point is reached, further cooling is retarded by the heat of vaporization set free when dew forms. If the dew point is above 40° F., the temperature will but seldom fall to freezing during the night.

217. Dew, fog, rain, and snow. On clear, still nights the ground radiates the heat that it has received during the daytime. The grass and leaves, which can radiate heat freely, cool rapidly and soon bring the air near them below its dew point. Then moisture condenses as **dew** or at lower temperatures as **frost.** This phenomenon is exactly like the formation of drops of water on a pitcher of ice water, or on one's spectacles when one comes from the cold outdoors into a warm room. Clouds covering the sky hinder the formation of dew because they lessen radiation. If the condensation of the moisture of the air is not brought about by contact with cold solid objects at the surface of the earth, but by great masses of cold air high above the

earth, clouds are formed and rain may result. **Fog** is merely a cloud touching the earth.

Clouds at very high altitudes may be composed of bits of ice, but, in general, clouds are made up of minute drops of water. Like particles of fine dust, very small drops of water tend to fall, but can do so only very slowly. Sometimes they fall into warm and not yet saturated layers of air, and then they change back again into vapor. Sometimes they are carried up by ascending currents of air faster than they can fall through them, and so seem to float. For example, the cloud of

Fig. 241. Snow crystals.

steam above a locomotive stack is composed of minute drops of water and yet rises with the warm air. Clouds are not durable. They simply mark a place in the atmosphere where condensation of water vapor is going on. In **rain** clouds the little particles of water come together and form drops, which easily overcome the resistance of the air and fall to the ground. If the temperature of the cloud is below 32° F., the particles of water unite to form little delicately fashioned hexagonal **snow crystals** (Fig. 241).

Snow and rain together make what the "weather man" calls "precipitation." Thus in New York there are about 150 days of rain or snow each year, and the total precipitation in a year, if it did not dry up, would cover the earth to a depth of about 3 feet. For agriculture it is necessary to have an annual total of eighteen or more inches, and this must be properly distributed throughout the year.

Questions and Problems

1. A room is 3 meters high, 10 meters long, and 6 meters wide. How many grams of water will be required to saturate the air at 20° C.?

2. An experiment showed that on a certain day, when the temperature was 30° C., the air contained 12 grams of water per cubic meter. What was the relative humidity?

3. How do undue dryness and undue dampness affect wooden furniture?

4. What change in the thermometer usually goes with a rising barometer?

5. What happens when a moist wind from the ocean strikes a mountain range?

6. In some hot countries the people cool their drinking water by setting it in jars of porous earthenware, in a shady place, where there is a current of air. Explain.

7. Why do clothes dry best on a windy day?

8. Why does sprinkling the street on a hot day cool the air?

9. Why is frost more likely to form on a still night than on a windy night?

10. Why does building smudge fires in an orchard tend to prevent frost?

11. Why does covering plants with papers tend to prevent frost?

Practical Exercise

Making a psychrometer. Fasten two thermometers to a narrow board and attach a strong cord to the upper end for whirling the psychrometer about your head. Fasten a single wrapping of muslin about one bulb and moisten with water. Whirl the thermometers until the wet thermometer ceases to fall. Determine the relative humidity from these readings of the wet- and dry-bulb thermometers and from the table which is furnished with the thermometers shown in figure 240. Find the humidity (1) on a clear day; (2) on a damp, cloudy day; (3) in the morning; and (4) in the afternoon of a clear day. Make a record of all your data and results.

218. Freezing by boiling. The fact that a large quantity of heat is needed to vaporize a substance is often made use of in getting low temperatures.

If a cylinder of liquefied carbon dioxide is tilted, as shown in figure 242, and the valve is opened, the liquid released from pressure boils very rapidly, cooling everything, including the rest of the liquid, so much that some of it is frozen. After the valve has been open a short time, the bag is filled with a white solid, frozen carbon dioxide. This solid evaporates very readily, and gives a temperature as low as $-80°$ C. If the solid is put in a beaker and mixed with ether, the mixture will freeze a test tube of mercury. The ether serves to carry the heat quickly from the test tube to the solid.

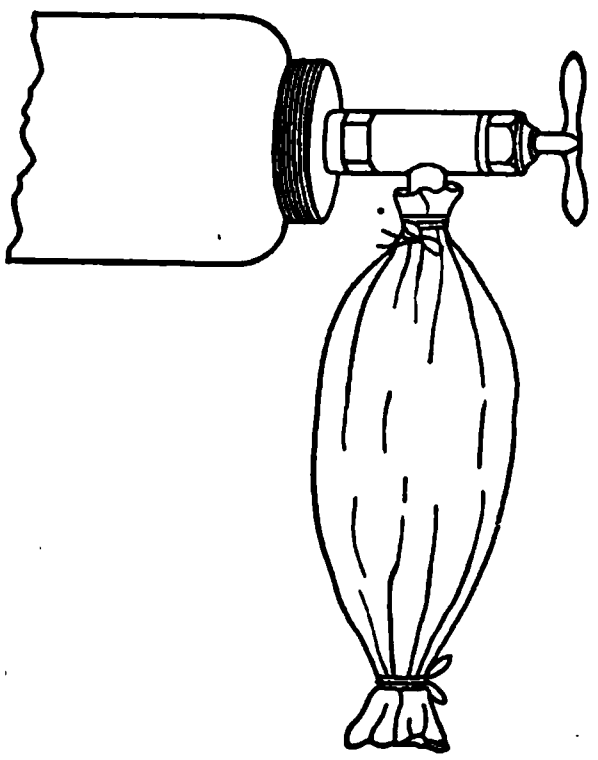

Fig. 242. Liquid carbon dioxide boiling and freezing.

219. Ice-making. In the manufacture of ice and in refrigerating plants (Fig. 243), gaseous ammonia is compressed by a pump and then cooled until it liquefies. During this process of compression and of condensation, heat is evolved, which is removed by passing the ammonia through a pipe covered with running water. The liquefied ammonia is then piped to the ice tank or cold-storage room, and allowed to ex-

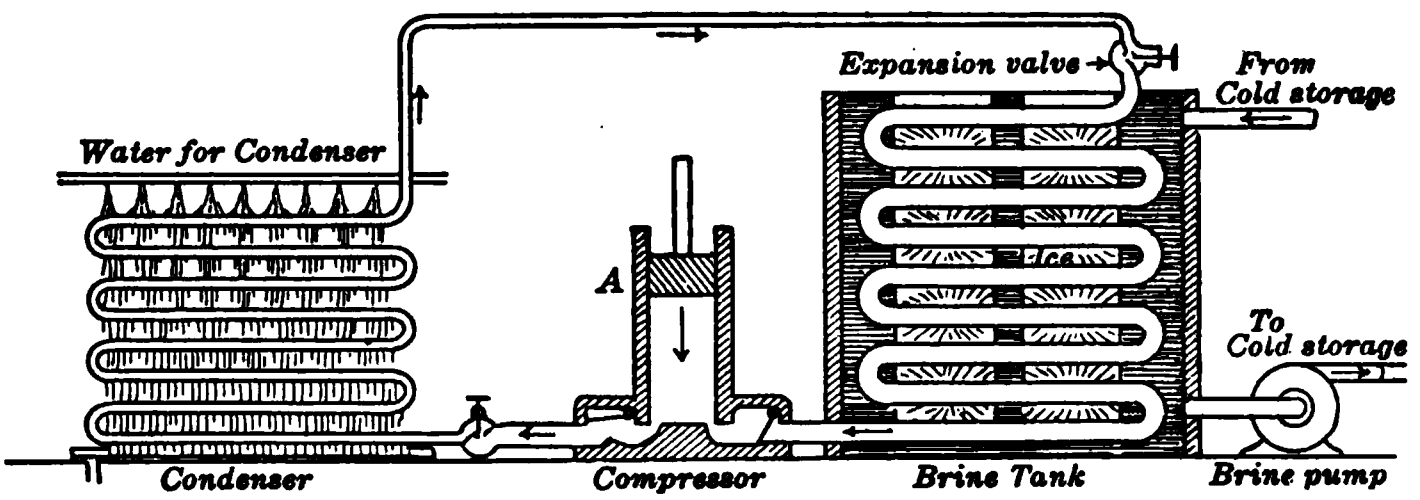

Fig. 243. Diagram of an ice-making plant.

pand through a valve with a small opening. This checks the flow, and so enables the pump to maintain enough pressure to keep the ammonia in liquid form on its way to the valve; while

beyond the valve the pressure is very small, so that the ammonia evaporates rapidly. While doing so, it absorbs heat from the refrigerating room. It is then ready to be compressed again.

In the manufacture of ice, the expansion pipes pass through a brine tank in which are smaller tanks of pure water. When the water in these tanks is frozen, the tanks are pulled up and the ice removed. The ammonia is used over and over again, but power must be constantly supplied to the compressor.

Iceless refrigerators for home use also have a small *compressor* run by an electric motor, *cooling coils*, an *expansion valve*, and *refrigerating coils*, which take the place of the ice. Some of them use ammonia; others use methyl chloride or sulfur dioxide in a similar way.

SUMMARY OF PRINCIPLES IN CHAPTER XI

Heat units:

1 calorie = heat to raise 1 gram of water 1° C.

1 B.t.u. = heat to raise 1 pound of water 1° F.

Specific heat = calories to raise 1 gram of substance 1° C.

= B.t.u. to raise 1 pound of substance 1° F.

Specific heat of water = 1 in either system of units.

Method of mixtures:

Heat given up by hot bodies = heat absorbed by cold bodies.

Pressure:

***Lowers* freezing point of water 0.0072° C. per atmosphere.**

***Raises* boiling point of water 0.037° C. per mm. of mercury.**

Heat of fusion = heat absorbed during melting,

= heat yielded during freezing.

Value for water, 80 calories.

Heat of vaporization = heat absorbed during evaporation,

= heat yielded during condensation.

Value for water, 540 calories.

$$\textbf{Relative humidity} = \frac{\textbf{actual moisture in air}}{\textbf{moisture in saturated air at same temp.}}.$$

QUESTIONS

1. If you know the dew point to be 10° C., how can you find the relative humidity at 20° C.?

2. Human hair when treated with ether is very sensitive to moisture. When it is moist it contracts, and when it dries it elongates. Explain how a moisture gauge, or " hygroscope," could be made with a hair.

3. Could gold money be cast instead of stamped with a die?

4. Why is a burn from live steam so much more severe than one from boiling water?

5. Why does one sometimes " catch cold " by sitting in a draft of cool air after taking violent exercise?

6. How low can the temperature fall during a rain?

7. Why can mercury mixed with zinc be purified by distillation?

8. Why is it difficult to make snowballs out of " dry snow "? What is " dry snow "?

9. What is the scientific fact back of the old saying that " a watched pot never boils "?

10. How would you determine the coldest spot in a refrigerator? Which foods should be put there?

11. Plot a curve to show the relation of calories to temperature in changing ice at −20° C. to steam at 120° C. (Make the scale 5 cal. = 1 mm. horizontal and 2° = 1 mm. vertical.)

12. Is a steam vent in a fireless cooker desirable? Why?

13. Illustrate from home experience four factors affecting rate of evaporation.

14. Why is ebonite chosen for the rod in an automatic air vent?

PRACTICAL EXERCISE

Moisture in the air of a room. Measure the dimensions, temperature, and relative humidity of your schoolroom, or of a room at home, and compute the total weight of water in the air of the room.

Pans of water are often placed over hot-air registers or hung close to radiators to humidify the air in the room. Try to find out how much water can be evaporated per hour in this way, and how much difference it makes in the relative humidity of the room. See *Packard*, Humidity Indoors (School Science, March, 1922)

CHAPTER XII

HEAT ENGINES

Importance of the steam engine — boilers — slide-valve and Corliss engines — condensers — efficiency — expansion — cylinder condensation — compounding — uniflow engine — steam turbines — gas engines — 4-stroke and 2-stroke engines — oil engines — mechanical equivalent of heat.

220. The importance of the steam engine. Until about two hundred years ago, the work of the world was done chiefly by the muscular energy of men and of animals, and occasionally by windmills and water wheels. This meant that no very large amount of power was available in any one place, and useful things were made in small quantities here and there by a great many independent artisans, each working for himself or with a small group of his friends.

The first successful steam engine was made in 1705 by **Thomas Newcomen**, an English blacksmith; it was used for pumping water out of a coal mine. Newcomen's engine (Fig. 244) was very crude and consumed a great deal of fuel for the work it did, but it was a great help to miners. Some seventy years elapsed without much change in steam engines. But then a Scotch instrument maker began an epoch-making career of invention and

Fig. 244. Newcomen's atmospheric steam engine.

improvement, that, in a single lifetime, gave to the world almost every essential feature of the steam engine of to-day. That man was **James Watt** (Fig. 245).

There resulted a tremendous change in the manner of life of the whole civilized world. Large amounts of power could be concentrated in a single plant, and this led inevitably to the factory system and ultimately to quantity production, like that of the Ford plant, which turns out over 4000 automobiles a day. Railroads and steamboats were developed to bring all parts of the world far closer together than ever before. And on the other hand, the factory system has crowded out the independent artisan and given us the labor problems of to-day. In all these ways the steam engine has affected human life much more than any other one machine or device ever invented.

Fig. 245. James Watt (1736–1819). Instrument maker at Glasgow University, famous for his improvements on the steam engine.

221. A modern steam plant. In a modern steam plant the steam is made in a boiler, is used in a steam engine, and is usually discharged into the air or into a condenser. We shall discuss these in turn.

222. Types of steam boilers. A good boiler should have great capacity for its bulk, and high efficiency. The **capacity** of a boiler means the amount of steam it can make per hour. For example, a modern freight locomotive makes over 50,000 pounds of steam an hour. Now the capacity of a boiler depends largely on the amount of heating surface it has, because only

about so much heat can flow per hour through each square inch of the wall between the fire and the water. For this reason

Fig. 246. Cross section of a modern locomotive. *G*, grate; *B*, firebox; *A*, brick arch to protect tubes from direct heat, *P*, fire tubes; *L*, throttle lever; *R*, throttle rod; *T*, throttle valve; *E*, exhaust pipe; *V*, piston valve; *C*, cylinder.

boilers are often made in very complicated shapes, so as to have as much heating surface as possible.

A locomotive boiler (Fig. 246) is a **fire-tube boiler**. This is a cylindrical shell filled with tubes, 3 or 4 inches in diameter, through which the fire and smoke pass. The water and steam fill the rest of the shell outside the tubes. Modern power plants use **water-tube boilers** (Fig. 247), which have the water inside the tubes and the fire and smoke outside. The tubes of such boilers are more or less inclined, and are fastened at each end into passages ("headers") which lead to a drum above; the tubes, headers, and the lower part of the drum are full of water; the remainder of the drum forms a space for steam. The fire is placed

Fig. 247. Water-tube boiler with superheater.

under the front end of the tubes; the products of combustion are deflected by brick walls so that they have to pass over the tubes two or three times before escaping up the chimney.

One improvement in modern boilers is the **automatic stoker**, which feeds coal into the grate a little at a time as it is needed. When the coal is pushed in from below, as shown in figure 248, the device is called an **underfeed stoker**. In some plants, coal is crushed to a dust and then blown in and burned at once. Sometimes **fuel oil** is sprayed in and burned under the boiler; this saves the expense of stokers and eliminates the ashes.

Fig. 248. Underfeed automatic stoker, which gives smokeless combustion.

223. Boiler draft. The capacity of a boiler also depends on the **draft** which is available to make the fire burn fiercely. It takes about 20 pounds of air to burn 1 pound of coal. To get a good draft, tall chimneys are sometimes used, and at other times a forced draft is made by a big fan. On battleships a forced draft is often obtained by making the whole fireroom, within which the stokers work, air-tight, and keeping it full of air under pressure, supplied by blowers or pumps as fast as it can escape through the fires.

224. Efficiency of boilers. Just as with any machine, the efficiency of a boiler is the output divided by the input. In this case the output is the heat in the steam delivered, and the input is the heat in the coal used. The efficiency of modern boilers ranges from 60 to 75 %. The hot gases in the chimney carry off a great deal of heat. A smaller amount of heat is lost by radiation from the fire box and boiler setting. Smoke pouring from the chimney means that just so much unconsumed fuel is going to waste, and, what is worse, is adding to the dirt in the atmosphere of the neighborhood.

225. Boiler accessories. Every boiler is equipped with a **steam gauge**, which is merely a Bourdon pressure gauge (section 76), and also a **water gauge** (section 61), which enables the engineer in charge to watch the water level in the boiler. If the water level is too low, there is danger of burning the tubes and plates and perhaps of wrecking the boiler; if it is too high, water is liable to be carried along with the steam and so damage the engine. Besides these devices, every boiler has a **safety valve**, which automatically blows off steam when the pressure exceeds a certain limit. A simple form of safety valve is shown in figure 249. In some forms a spring is set so as to release some steam if the pressure becomes too great inside the boiler.

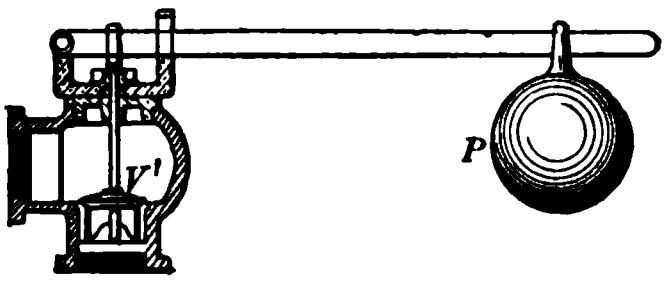

Fig. 249. Safety valve for a boiler.

QUESTIONS

1. Which type of boiler is ordinarily used with the small "donkey" engines that operate derricks?

2. Which type of boiler is used on a steam-driven automobile?

3. How does the principle explained in section 181 apply to the water-tube boiler in figure 247?

4. In some marine boilers, called Scotch boilers, the fire box is inside the shell and completely surrounded by water except where the coal and ash doors are. What is the advantage of this type of construction?

5. How much of the fire box of a locomotive is surrounded by water?

226. Two types of steam engine. The engine most commonly used in small plants is the **slide-valve engine** (Fig. 250). Steam comes from the boiler into the steam chest C, and then into the working end A of the cylinder through a passage shown by the arrows at the right of the picture. At the same time the spent steam in the other end B of the cylinder is passing through the hollow interior of the valve, to the exhaust passage E. It then escapes to the air, or to the condenser, through a pipe at the back, not shown in the figure. At the end of the stroke the valve is pulled far enough to the right to admit live steam to the left-hand end of the cylinder, while the spent steam in the right-hand end escapes into the exhaust. The slide valve is pushed back and forth by a so-called **eccentric**. This is a circular disk which is set on the main shaft a little off center. The wobbling motion of the eccentric is communicated to the slide-valve rod by means of a collar.

Fig. 250. Slide-valve steam engine.

Fig. 251 Corliss steam engine.

In large steam engines **Corliss valves** are more often used. A Corliss valve (Fig. 251) opens and closes by *turning* a little

in its seat. In a Corliss engine there are four such valves — two at each end of the cylinder. Two of them, N and O, are for admitting the steam, and two, P and Q, for letting the steam out. When valve N is open to admit steam, valve Q is also open to let steam out of the other end of the cylinder, while O and P are closed; on the reverse stroke, O and P are open, while N and Q are closed. These valves are automatically opened and closed at the proper time by the engine itself. The fact that the time at which each valve opens can be accurately adjusted independently of the other valves makes Corliss engines more efficient than slide-valve engines.

227. Condenser. When its exhaust pipe opens directly into the atmosphere, an engine is called a **non-condensing** engine. The power depends on the excess of the steam pressure in the boiler above that of the atmosphere outside. Ordinary locomotives and most small engines are of this type. In fact, the locomotive depends on the puffs of escaping steam, which blow smoke up the stack ahead of them, to furnish a draft for the boiler.

Greater economy is obtained by sending the exhaust steam to a vacuum chamber, or **condenser.** In one type the steam coming from the engine is condensed by a jet of cold water, and in another type it is condensed in a large steel box filled with tubes through which cold water is circulated. A small pump is used to pump out the condensed steam, as well as any air which may have leaked in. Such engines are known as **condensing** engines. Marine engines are almost always condensing engines, so that the condensed steam can be put back into the boilers, which would soon be ruined if supplied with salt water.

228. Efficiency of a steam plant. We have already seen that the modern steam boiler has an efficiency of about 70%; but there are still larger losses in the engine itself. The escaping steam from an engine always carries away a large amount of unutilized heat energy. It can indeed be proved that the greatest efficiency possible for a steam engine running with a boiler pressure of 163 pounds is only 18.5%.

It must be remembered that this 18.5% is the efficiency of the engine alone, so that the efficiency of the engine and boiler would be 18.5% of 70%, or only about 13%. This means

that about 87% of the energy of the coal would not be converted into mechanical energy. By using very high temperatures, the best engines have been made to utilize about 20% of the energy originally in the coal. The ordinary locomotive, however, does not utilize more than 8%.

229. Expanding steam. If live steam from the boiler is allowed to push the piston through its entire stroke, and is then thrown away, that is, is allowed to pass into the atmosphere or into a condenser, it is evident that much energy is wasted. To get more work out of the steam, the valve is closed after the piston has made about $\frac{1}{4}$ or $\frac{1}{3}$ of its stroke, and the steam is allowed to **expand** through the rest of the stroke. The pressure and the temperature of the steam drop rapidly after " cut-off."

230. Cylinder condensation. When the exhaust valve of a steam engine opens, there is a sudden drop in the pressure of such steam as cannot immediately escape, and its temperature is much lowered. Then, as the piston returns, this cooler steam is pushed up into the end of the cylinder and cools the metal walls there. When the next charge of high-pressure hot steam from the boiler comes in, it has to warm the walls again, and a good deal of steam is condensed in the process. This **cylinder condensation** is one of the important causes of inefficiency in steam engines.

231. Compound engines. Cylinder condensation can be much reduced by using the steam first in a small high-pressure cylinder with a small drop in pressure; the exhaust from this cylinder is then passed into a larger intermediate-pressure cylinder, where it undergoes another small drop in pressure; the steam finally passes to a third low-pressure cylinder, where a third small drop in pressure brings it down to the pressure at which it is to be discharged. In such an engine, called a **triple-expansion** engine, the range of temperature in any one cylinder is reduced to about one third, and losses due to cylinder condensation are much reduced. Sometimes only two cylinders are used, and such an engine is called a **compound engine**; occasionally the steam is used in four cylinders, one after the other, in what is called a **quadruple-expansion engine.**

232. Uniflow engine. The plan in this very modern type of steam engine is to make most of the cooler steam flow out of the cylinder at the middle. In other words, the *steam flows out of the cylinder in the same direction in which it enters;* hence the name, **uniflow.**

Figure 252 shows a piston *P* nearly half the length of the cylinder. Around the middle of the cylinder is a row of slots in the wall, and at this point the cylinder is surrounded by a ring-shaped channel which is connected with the condenser through the pipe *E*. The steam enters one end of the cylinder through the valve *B* and pushes the piston forward. As soon as the piston uncovers the slots in the middle of the cylinder, the steam escapes through these into the condenser. But at the same time the engine has closed valve *B* and opened valve *A* at the other end of the cylinder. The steam now pushes the piston back again until it again uncovers the exhaust slots in the middle. Each time that the piston starts back, it traps a considerable amount of steam and compresses it nearly to boiler pressure, thus helping to keep the admission ends of the cylinder warm.

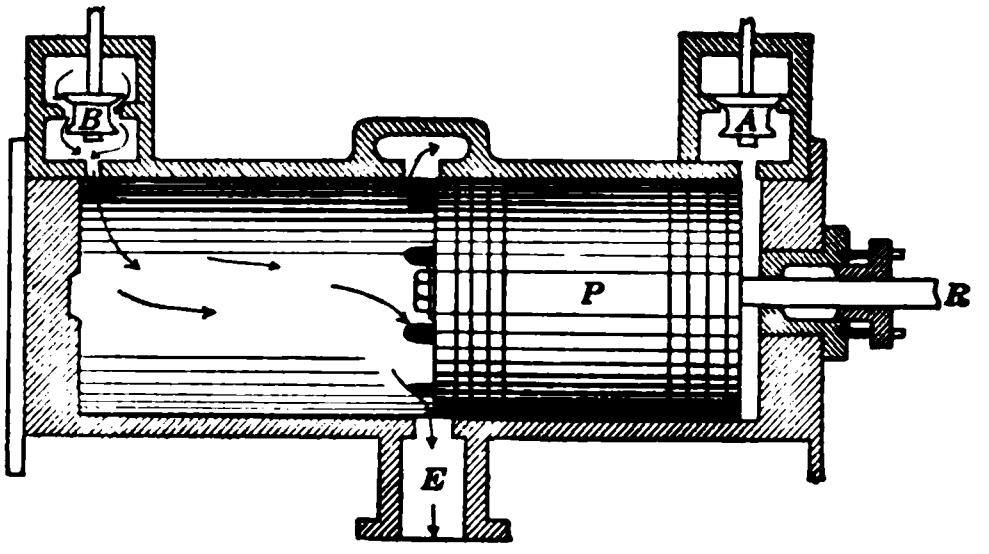

Fig. 252. Diagram of a uniflow steam engine.

QUESTIONS AND PROBLEMS

1. Why does the water in a locomotive not boil at 100° C.?

2. Why are not the "superheater" pipes in figure 247 placed directly over or beside the fire itself?

3. The area of the piston of a steam engine is 120 square inches and its stroke is 2 feet. If the "mean effective pressure" of the steam is 50 pounds per square inch, what is the total force exerted on the piston?

4. In problem 3, how many foot pounds of work are done in one revolution of the shaft (two strokes)?

5. If the engine in problem 3 is making 150 revolutions per minute, what is its "indicated horse power"; that is, what is the rate in horse power at which the steam does work on the piston?

6. There is a well-known formula that is often written

$$2\frac{PLAN}{33000}$$

where P is the "mean effective pressure" in a cylinder, in pounds per square inch, L is the length of the stroke in feet, A is the area of the piston in square inches, and N is the r.p.m.

(*a*) Of what quantity does the formula give the value? Prove your answer.

(*b*) Can you explain why such a queer mixture of foot units and inch units is used?

7. A locomotive with cylinders 27 inches in diameter and a stroke of 2.5 feet is provided with driving wheels 5 feet in diameter. If the mean effective pressure of the steam in the cylinder is 60 pounds per square inch, and the engine is making 50 miles an hour, what is the indicated horse power?

8. How much mean effective steam pressure will be needed to get 10 horse power from a "donkey engine" running at 200 revolutions per minute? (Assume area of piston to be 50 square inches, and stroke 1 foot.)

9. Piston valves (Fig. 253) are now ordinarily used on steam engines, especially locomotives. How do they work?

Fig. 253. Piston valve used on modern steam engines.

Practical Exercise

Running a steam engine. Examine carefully the parts of a small boiler and engine. Be sure that you understand the use of each part of the demonstration model. Fill the boiler about three-fourths full of water and heat by means of a gas-burner in the fire box. When you have sufficient steam pressure, open the valve between the boiler and engine and run the engine. How would you determine the efficiency of the model plant?

233. Steam turbine. Thus far we have been describing **reciprocating** engines, in which the back-and-forth motion of the piston rod is turned into rotary motion by means of a crank and connecting rod. Since the piston must come to a standstill at the end of each stroke, this means, in high-speed engines, very frequent starting and stopping, which causes so much shaking as to require big and expensive foundations.

On steamships the continual jarring causes a disagreeable vibration. In recent years a new and distinctly different type of engine, the **steam turbine**, has been developed, in which there is no reciprocating motion.

294. De Laval steam turbines. In this turbine (Fig. 254) there are one or more **nozzles** in which steam expands from boiler pressure to atmospheric pressure, forming a jet of steam moving at a speed of from 35 to 45 miles a minute. There is also a **wheel** provided with curved blades, called **buckets**, against which the jets of steam impinge. The rim speed of these wheels is between 15 and 20 miles a minute, and so the disks must be made of the best steel and very carefully shaped and balanced, and the buckets must be very firmly fastened in. These wheels rotate very fast, sometimes as fast as 70,000 r. p. m., so that only cream separators can be run from the same shaft. For other purposes large reduction gears (Fig. 255) are used.

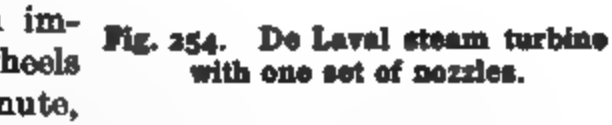

Fig. 254. De Laval steam turbine with one set of nozzles.

Fig. 255. De Laval reduction gears, ratio 10 to 1.

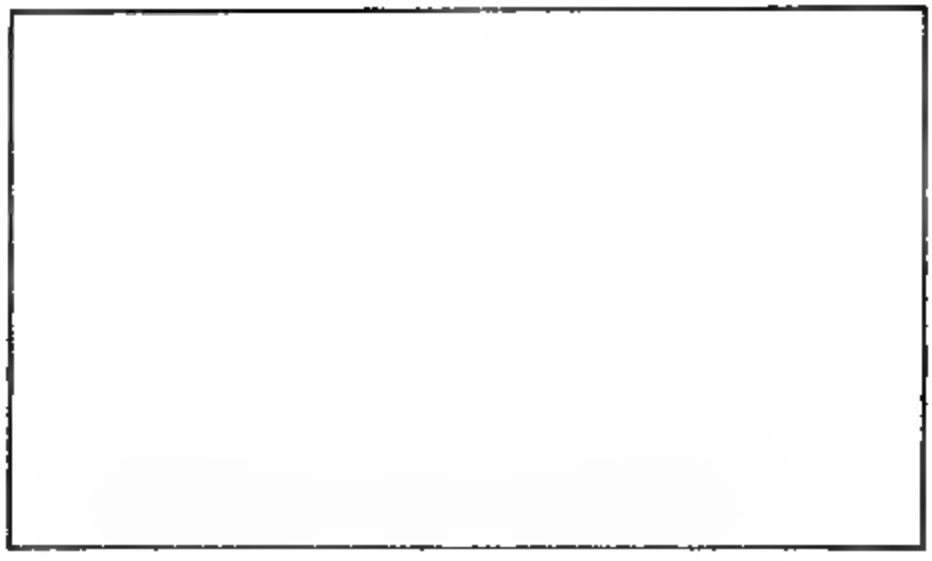

Fig. 256. Rotor of a modern Curtis turbine. A wheel with 3 rows of blades in process of construction.

235. Curtis turbines. These turbines are made to run at lower speeds by mounting from 2 to 40 separate turbine wheels in little boxes or cells, each with its own set of nozzles, on a single shaft. The steam from the boiler flows through all these boxes, or **stages**, one after the other; in each stage there is only a small drop in pressure, and the steam jets have much lower speeds than in a De Laval turbine, thus permitting much lower wheel-speeds.

Sometimes, as in the older Curtis turbines, each jet has two or three chances at a given wheel. After its first passage through a row of buckets it escapes with a velocity which, although smaller than in the

Fig. 257. Westinghouse steam turbine (Parsons type) with the upper half of its casing lifted.

nozzles, is still high; the stream of steam is then picked up by some stationary blades attached to the casing, turned around, and made to impinge again either on the same set of buckets, or on another row of buckets attached to the rim of the same wheel (Fig. 256).

236. Parsons turbines. In this turbine (Fig. 257) not all of the drop in pressure in a given stage occurs in the nozzles. Enough drop

does occur, however, in the nozzles to shoot the steam into the rapidly moving buckets without shock; then the steam experiences a second drop in pressure in the buckets themselves, more velocity is generated, and the steam is shot out backward from the exit side of the buckets. This action tends to push the buckets in the opposite direction, just as water escaping from the arms of a lawn sprinkler (Fig. 258) pushes the arms around. Parsons turbines (Fig. 259) commonly have a great many rows of moving buckets, or blades, sometimes several hundred, mounted on a cylindrical or cone-shaped "rotor" instead of on separate wheels, so that they look quite different from other turbines; but the fundamental principles involved are much the same for all types of turbines.

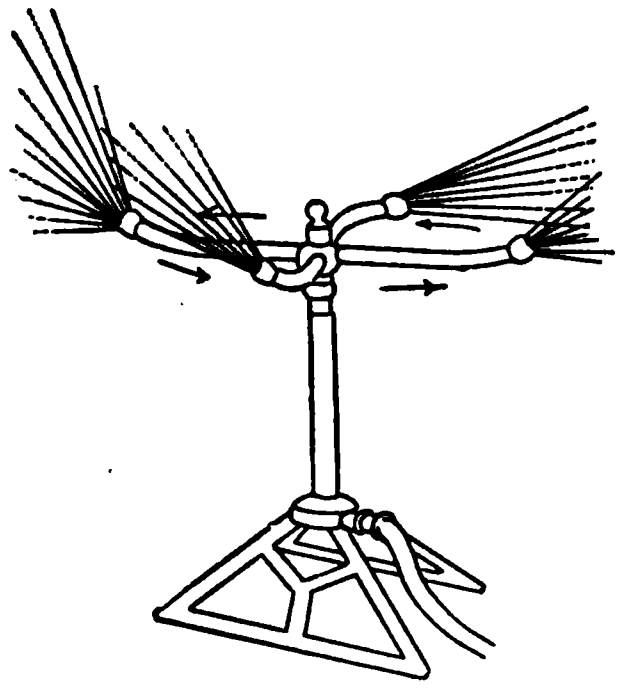

Fig. 258. Lawn sprinkler illustrates the reaction type of steam turbine.

237. Gas and oil engines. The essential difference between a steam engine and a gas or oil engine is that in the case of the steam engine the fuel is burned under a boiler and the working substance, steam, is conducted to the engine in pipes; while in the case of the gas or oil engine the fuel is burned in the cylinder of the engine itself and the hot products of combustion are themselves the working substance. In other words, the gas engine is an **internal-combustion** engine.

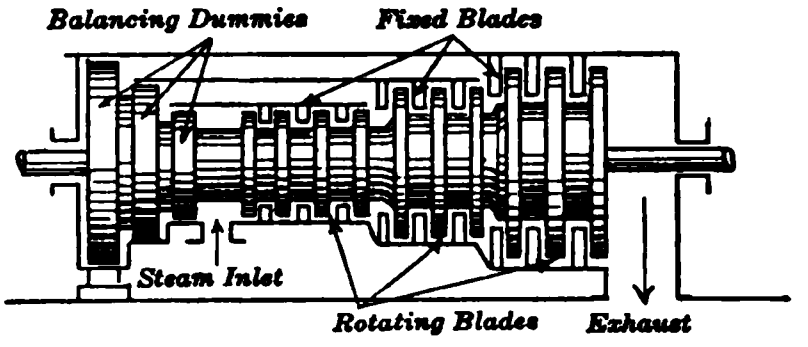

Fig. 259. Diagram of a Parsons turbine.

The first engines of this type used ordinary illuminating gas for **fuel**; this is the origin of the name "gas engine." Nowadays liquid fuels are chiefly used, particularly gasoline in automobiles and motor boats, kerosene in farm tractors, and sometimes crude oil or even fuel oil (*i.e.* crude oil from which the gasoline and kerosene have been removed) in the modern

Fig. 260. Three large gas engines run by blast-furnace gas. Each engine has two cylinders set end to end, the two pistons being on one long piston rod running through both ends of each cylinder. The half-time shaft that works the valves is plainly visible.

oil engine. Some true gas engines are still in use, running on producer gas made from coal, or on the gas produced by blast furnaces (Fig. 260).

238. The carburetor. This is a device for changing a liquid fuel, such as gasoline or kerosene, into a vapor and mixing it with air in the proper proportion for complete combustion. Probably the simplest type of carburetor is the one shown in figure 261. Here a shallow pool of gasoline forms in the bottom of the U-shaped air passage, and when just the right amount has flowed in, the needle valve is closed by the rising of the float. Then a puff of air is drawn over the surface of the pool and picks up the gasoline partly as vapor and partly as spray.

Fig. 261. Section through a puddle type of carburetor.

Most modern carburetors are of the spray or nozzle type, in which a jet of gasoline is sprayed into a current of air to form an explosive mixture. Figure 262 shows the principle of the spray carburetor. The commercial carburetor of to-day has to vaporize less volatile liquids than formerly, has to operate in winter as well as in summer, and has to provide the proper mixture for high speeds as well as for low speeds. For these reasons the modern carburetor is a delicate and complicated piece of mechanism.

Fig. 262. Diagram illustrating principle of jet type of carburetor.

239. Cooling the gas engine. Since the cylinder of the gas engine has to be a furnace as well as a cylinder, it would get dangerously hot if it were not cooled from the outside. It may be **water-cooled** by surrounding it with a jacket in which water is circulated. Figure 216 shows the convection currents of water in the cooling system of an automobile. The water heated in the cylinder jackets rises and flows over into the top part of the radiator, where it is cooled. It is then carried back from the lower portion of the radiator to the engine cylin-

Fig. 263. Air-cooled automobile engine.

der. In many automobiles this natural convection current is helped by a centrifugal pump, and in this case a lighter radiator and less water may be used than in the convection system.

It is possible to have the cylinders of a gas engine **air-cooled** by giving them a corrugated outer surface which radiates heat rapidly, and by forcing a stream of air over this surface. This system of cooling is used on motor cycles, on a few automobiles (Fig. 263), and on rotary airplane engines.

240. How the gas engine works. Nearly all gas engines are driven by **explosions** which take place within the **cylinder** of the engine and drive the **piston**, this motion being transmitted

through the **connecting rod** to the **crank shaft**. These explosions are quite like the explosion of gunpowder in a gun. A mixture of gas and air is taken into the closed end of the cylinder and then ignited; the explosion is an almost instantaneous combustion, producing a very high temperature and a corresponding increase in pressure.

We may illustrate the explosive force of a mixture of gas and air by pouring a few drops of gasoline into an empty tin can. (The amount to be used depends on the size of the can and may be determined by trial.) An ordinary automobile spark plug is inserted in the side of the can (Fig. 264), which is then covered and shaken in order to vaporize the gasoline and mix it with air. A spark is then made to pass between the plug terminals by means of an induction coil. If there is the proper proportion of gas and air in the can, there will be an explosion which will blow off the cover.

Fig. 264. Exploding a mixture of gasoline vapor and air with an electric spark.

After the explosion of the gases in an engine, the products of combustion must be got rid of and a fresh charge of gas and air must be taken in for the next explosion. There are two ways of performing this operation. One is used in *four-stroke* engines, which have an explosion once in four strokes or two revolutions, and the other, in *two-stroke* engines, which have an explosion once in two strokes or one revolution.

241. The four-stroke engine. This is the form most commonly used for automobiles and for stationary engines. There are two valves in the end of the cylinder (Fig. 265): an **inlet valve** A, which admits the mixture of gas and air from the carburetor; and the **exhaust valve** B, which opens into an exhaust manifold, from which the spent gases are discharged through a **muffler** (or silencer) into the atmosphere. A **spark-plug** is inserted in the closed end of the cylinder for the ignition of the mixture.

The engine works in the following way. On the first stroke, called the **suction stroke** (Fig. 265 (*a*)), the inlet valve is open and, as the piston descends, a fresh charge of gas and air is drawn in. On the next stroke, called the **compression stroke** (Fig. 265 (*b*)), the piston rises with both valves closed and the gas is compressed to from $\frac{1}{7}$ to $\frac{1}{8}$ of its original volume. Just as the piston gets to the top, the ignition system, under the control of a "timer," shoots a spark across the gap of the spark plug and an **explosion** takes place. The piston is pushed down by the high pressure exerted by the very hot gases expanding behind it. This is called the **expansion** or **working stroke** (Fig. 265 (*c*)). Just as the piston reaches the bottom the exhaust valve is opened, and the burned gases are forced out while the piston moves up. This is the **exhaust stroke** (Fig. 265 (*d*)).

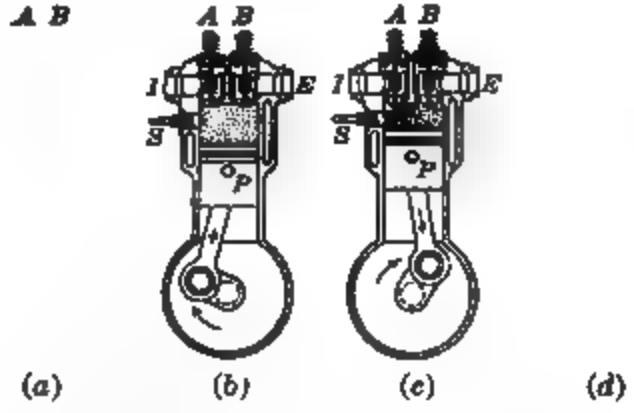

Fig. 265. Four strokes of a gas engine: (a) suction, (b) compression, (c) explosion or working, and (d) exhaust stroke.

The four strokes are, then, (1) suction stroke, (2) compression stroke, (3) working stroke, and (4) exhaust stroke. These four strokes constitute one complete **cycle** or round of action. The whole cycle requires 2 whole revolutions of the crank shaft for its completion. Since power is obtained only on every alternate outward stroke, a heavy flywheel is used to keep the engine going during the other 3 strokes. In automobile and airplane engines, 4, 6, 8, or 12 cylinders are used to drive a single crank shaft, and are so timed that one or the other of them is delivering power all the time (Fig. 266).

242. The two-stroke engine. This form of engine (Fig. 267) is often used on motor boats. The explosive mixture is taken into an air-tight crank case and slightly compressed on the downstroke of the piston. As the piston nears the bottom of its stroke, it uncovers first the **exhaust port** *E*, letting part of the spent gases in the cylinder blow off, and then the **trans-**

fer port *B*. The slightly compressed charge in the crank case then rushes into the cylinder, sweeping out the rest of the exploded gases before it. On the upstroke of the piston the ports are covered and the fresh charge is compressed. As the

Fig. 266. A four-cylinder automobile engine partly cut away to show pistons P, valves VV, spark plug S, crank shaft C, connecting rod CR, cam shaft CS, water jacket W, oil pump OP, and flywheel F.

piston passes its upper dead center (or soon afterward), the charge is exploded. The only true valve in this engine is a light check valve, where the fresh gases enter the crank case. The disadvantage of this type of engine is that some of the fresh gas is lost with the spent gases through the exhaust, so that it uses more gasoline than some other types. But, on the other hand, it is very simple and gives a push every revolution.

243. Control of gasoline engines. The power delivered by a gas engine can be varied within wide limits by means of a throttle. This valve is usually of the butterfly type (much like a damper in a stove pipe), and is placed in the outlet pipe of the carburetor so as to change the amount of mixture that the engine receives during each suction stroke.

A second way of changing the power is by varying the time of the explosion. If the explosion does not come at the upper dead center, but part way down the expansion, or working, stroke, the power yielded is much less. This is done to make an engine run slowly. Adjusting the electrical connections so as to bring the time of explosion nearer the upper dead center is called **advancing the spark**. Running on a "retarded spark" wastes gasoline, because the amount used per stroke is the same as at full power. The greatest economy of fuel will result when the engine is driven with as little throttle opening as possible and with the greatest spark advance the motor speed will allow.

Fig. 267. Two-stroke gas engine.

Practical Exercise

Ford engine. Study the construction and operation of the Ford engine as outlined in *Good's* Laboratory Projects in Physics (Macmillan). If your school laboratory does not have such an engine for demonstration, visit an automobile repair shop.

244. Oil engines. Almost any gasoline engine will operate for a time on kerosene, provided it has been started and thoroughly warmed up on gasoline. But the engine will not be likely to run very long unless the carburetor is specially designed for this less easily vaporized fuel. However, **kerosene** engines are now successfully used on many farm tractors (Fig. 268).

When crude oil is used as a fuel, pure air is drawn into the cylinder, rapidly compressed, and thereby greatly heated.

Then the fuel is sprayed directly into the cylinder. In the Diesel engine (Fig. 269) the oil is blown in by an auxiliary stream of highly compressed air. In another type of oil engine (Fig. 270), the fuel is pushed out of a little cup in the cylinder by the explosion of some air from the cylinder itself; this air is trapped while being compressed, and blows out again as soon as the piston begins to move back. Neither the

Fig. 268. Farm tractors often use kerosene as well as gasoline for fuel. These "cross-country locomotives" are used in hauling freight, in road building, and in logging. In the World War tractors in a modified form were used as "tanks."

Diesel nor the other oil engine needs a carburetor or a spark plug because the oil begins to burn as soon as it comes in contact with the highly compressed hot air. These engines are built in both 4-stroke and 2-stroke types.

Diesel engines are used to drive submarines and freight ships, because they are economical in the use of fuel, need no large funnels, and eliminate smoke, cinders, and ashes. How-

ever, these engines require a plentiful supply of compressed air for starting and maneuvering, and are more difficult to keep in repair than steam engines. The other oil engine is com-

Fig. 269. Four-cylinder Diesel type of oil engine. This unit (rated at 585 horse power) supplies power to a large flour mill by means of a rope drive. It is also direct-connected to an electrical generator.

monly used for small-power purposes, such as driving farm machinery.

245. Mechanical equivalent of heat. We have been considering the efficiency of engines without stopping to describe how it is measured. Evidently we must have some way of comparing the output, which would naturally be measured in foot pounds or kilogram meters, with the input, which would naturally be measured in B.t.u. or calories. This involves finding a definite relation between a foot pound and a B.t.u.,

or between a kilogram-meter and a calorie. This problem was not solved until about the middle of the last century, when an Englishman, Joule, did his famous experiment of churning water.

He arranged a paddle wheel in a box of water (Fig. 271). The paddles were turned by weights which descended and thus unwound cords on the spindle of the wheel. The water was kept from following the rotating paddles by fixed paddles which projected from the sides of the box.

Fig. 270. Section of the cylinder of a "solid-injection" oil engine.

In this experiment the mechanical work put in could be measured by multiplying the weights by the distance through which they fell; and the heat produced could be measured by multiplying the weight of the water by the rise in temperature. Great care was taken to prevent any loss of heat. The result of this and many other experiments of a similar nature led Joule to announce the principle: *The number of units of work put in is always proportional to the number of units of heat produced.*

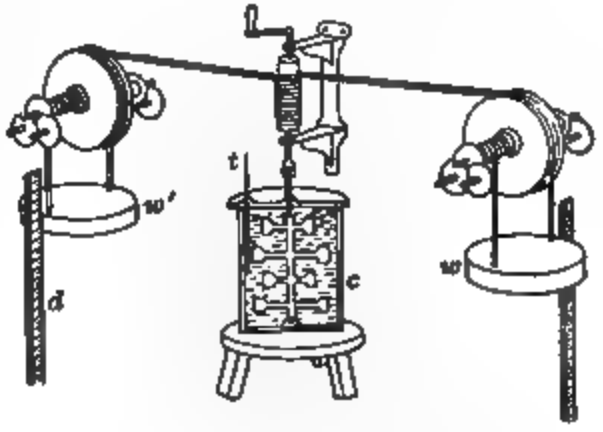

Fig. 271. Joule's machine for measuring the mechanical equivalent of heat.

As a result of Joule's experiments, of the more accurate experiments of Rowland in Baltimore, Md., and of many others, it appears that *778 foot pounds of work are equivalent to the heat required to raise one pound of water one degree Fahrenheit*, or that *the energy required to heat one kilogram of water one*

degree centigrade is equal to the work done in raising one kilogram to a height of 427 meters.

1 B.t.u. = 778 foot pounds of work.

1 kilogram calorie = 427 kilogram meters of work.

To compute the efficiency of an engine we have, therefore, to divide the work done by the heat put in, *expressing both in the same units* by means of the above relationships.

This work of Joule's was a decisive argument in favor of the principle of the conservation of energy, for it meant that heat and work are but different forms of energy.

PROBLEMS

1. The Falls of Niagara on the American side are about 165 feet high. If no energy were lost by radiation by the water on the way down, or turned into latent heat by the evaporation of spray, how much warmer would the water be in the river below the falls than at the top? (Hint: Consider 1 pound of water.)

2. If a horse power is equal to 33,000 foot pounds of work per minute, how many foot pounds are there in a horse-power hour; that is, in the total amount of work produced by a 1-horse-power engine working for one hour?

3. A pound of average coal yields 14,000 B.t.u. when burned. To how many foot pounds is this heat equivalent?

4. From the results of problems 2 and 3, calculate the horse-power hours per pound of coal if all the heat energy could be turned into work.

5. A test of a certain steam engine showed that 1 pound of coal generated 1 horse-power hour; from the three preceding problems compute the efficiency.

6. The overall efficiency of a certain steam plant is 15%, and it runs steadily for $7\frac{1}{4}$ hours each day delivering 2334 horse power. How many tons of coal must be burned per day?

7. If a ton of coal costs $7.00, what does the fuel cost to run for one hour a 1556-horse-power locomotive whose efficiency is 8%?

8. If a gallon of gasoline yields 110,000 B.t.u. when burned, and the efficiency of an automobile engine is 20%, how many horse-power hours will a gallon produce?

9. If an automobile can average 20 miles per gallon of gasoline at 24 miles an hour with an engine the average output of which is 10 horse power, what is the overall efficiency of the car?

SUMMARY OF PRINCIPLES IN CHAPTER XII

The mechanical equivalent of heat is the value in foot pounds of one B.t.u. or in kilogram meters of one calorie.

$$1 \text{ B.t.u.} = 778 \text{ ft. lbs.}$$

$$1 \text{ kg. cal.} = 427 \text{ kg. meters.}$$

$$\text{Efficiency} = \frac{\text{output}}{\text{input}}.$$

Both must be expressed in the *same unit*.

QUESTIONS

1. Why does a steam jacket increase the efficiency of a steam engine?

2. Does a water jacket increase the efficiency of a gasoline engine?

3. How are the cylinders of engines lubricated?

4. How does a ship equipped with steam turbines reverse its propellers?

5. Is an ordinary gas engine self-starting? How are automobile engines made self-starting?

6. Why is a system of gears, known as the transmission (Fig. 272), used in an automobile to connect the crank shaft of the engine with the driving shaft?

Fig. 272. Transmission gears used on an automobile.

7. How would you compute the efficiency of a gun regarded as a heat engine?

8. Why does a high-speed turbine give more power than a low-speed reciprocating engine of about the same size?

9. What is the use of the radiator on an automobile? Describe its construction.

CHAPTER XIII

MAGNETISM

The lodestone — magnetic poles — attraction and repulsion — the compass and the magnetism of the earth — magnetic field — induced magnetism — permeability — uses of permanent magnets — theory of magnetism.

246. The lodestone. For many centuries it has been known that a certain kind of rock, called the lodestone, has the power of attracting iron filings and small fragments of the same rock. Its abundance near Magnesia in Asia Minor led the Greeks to call it "magnetite" or "magnetic" iron ore.

We may take a piece of magnetite (Fe_3O_4) and show that it picks up pieces of iron (Fig. 273), but does not pick up copper or zinc. We can magnetize a knitting needle by stroking it with a piece of magnetite.

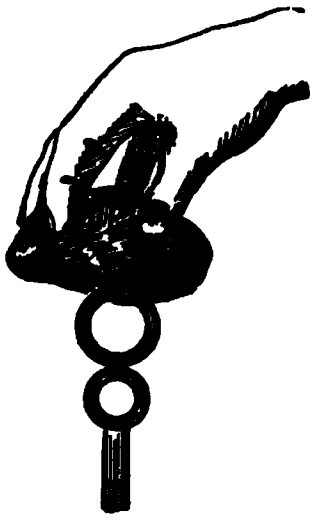

Fig. 273. Lodestone attracts iron.

This kind of iron ore occurs in many places in this country as well as in Norway and Sweden. When a steel bar is rubbed with such a natural magnet, the steel itself becomes magnetic and is then called an artificial magnet. In a later chapter we shall learn how to make magnets by using an electric current.

247. Magnetic poles. It was a good many years before anyone in Europe noticed that the magnetic property of a lodestone is concentrated more or less definitely in two or more spots, and that if a somewhat elongated lodestone with only two of these spots, and those near its ends, is hung by a thread, it will set itself with one spot toward the north and the other toward the south. We now use magnetized needles

instead of lodestones, and call such an arrangement a **compass** (Fig. 274); we all know how valuable this instrument is to mariners, explorers, and surveyors. Probably the Chinese had compasses many years before Europeans reinvented them.

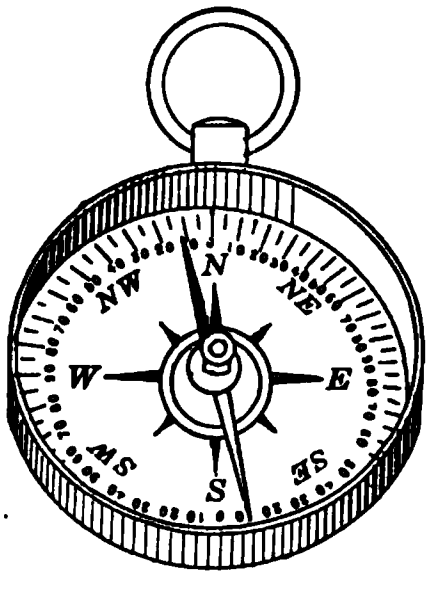

Fig. 274. Pocket compass.

The two spots which point, one to the north and one to the south, are called the **poles** of the magnet; one is called the **north-seeking** pole (N) and the other the **south-seeking** pole (S)

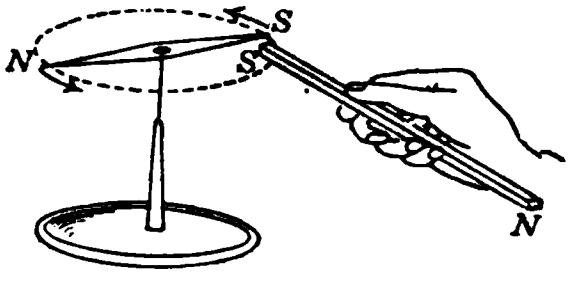

Fig. 275. Like magnetic poles repel each other.

248. Magnetic repulsion. It was many centuries after people had known that magnets would attract things before they learned that magnets sometimes repel things.

If we bring the south-seeking or S-pole of a magnet near the S-pole of a suspended magnet, the poles repel each other (Fig. 275). If we bring the two N-poles together, they also repel each other. But if we bring an N-pole toward the S-pole of the moving magnet, or an S-pole toward the N-pole, they attract each other.

That is,

Like poles repel each other,
Unlike poles attract each other.

Experiment shows that these *attractive or repulsive forces between magnetic poles vary inversely as the square of the distance between the poles.*

249. Declination and dip. Soon after the compass was invented, it was noticed that it did not point true north and south. For a long time it was supposed that this deviation, or **declination**, was everywhere the same, until Columbus, on his way to America in 1492, discovered near the Azores a place of no declination. Evidently an exact knowledge of the decli-

nation at different places is of the greatest importance to mariners and surveyors, and so careful maps are published by the different governments giving lines of equal declination. Figure 276 shows such a map. From this map it will be observed

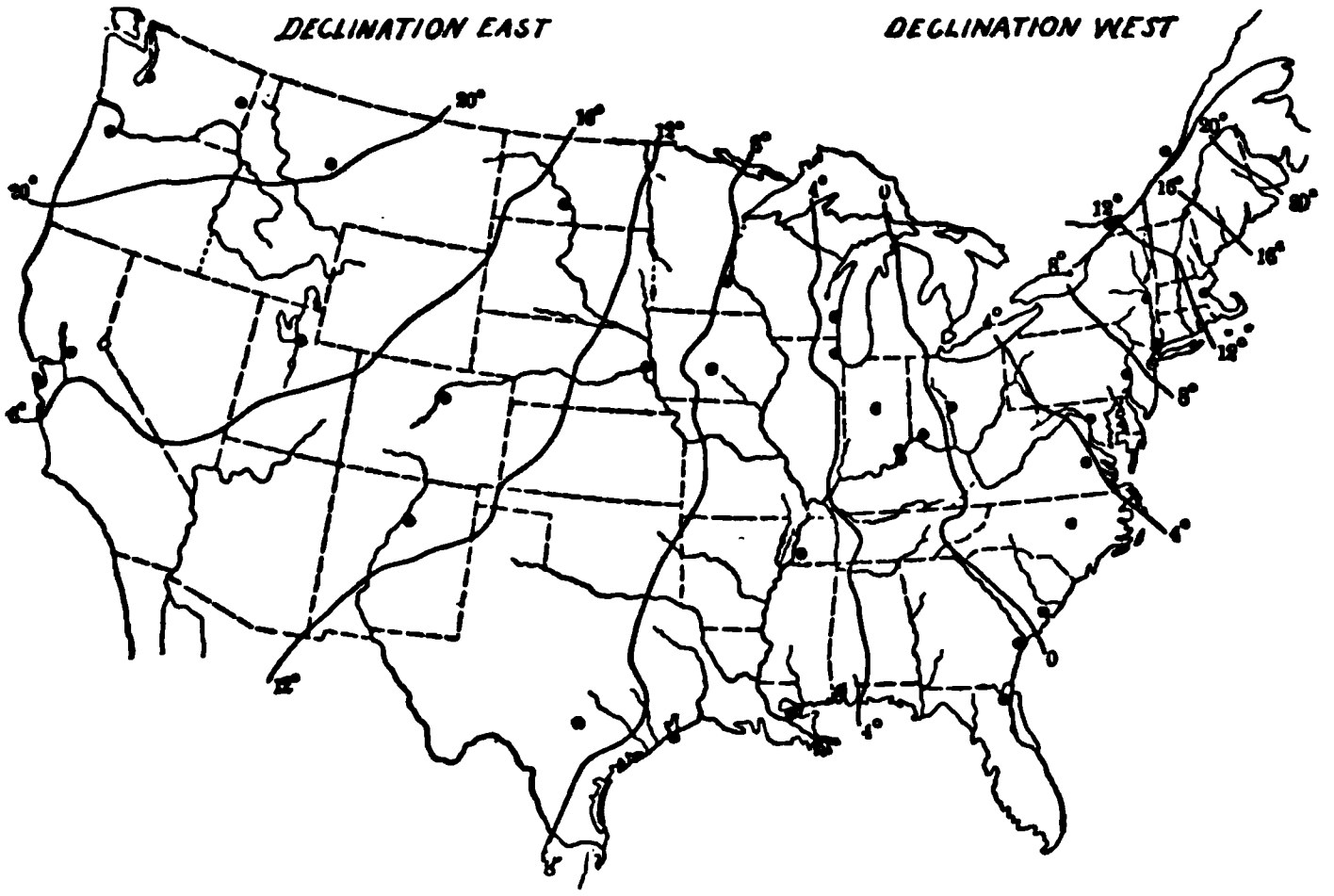

Fig. 276. Map showing declination.

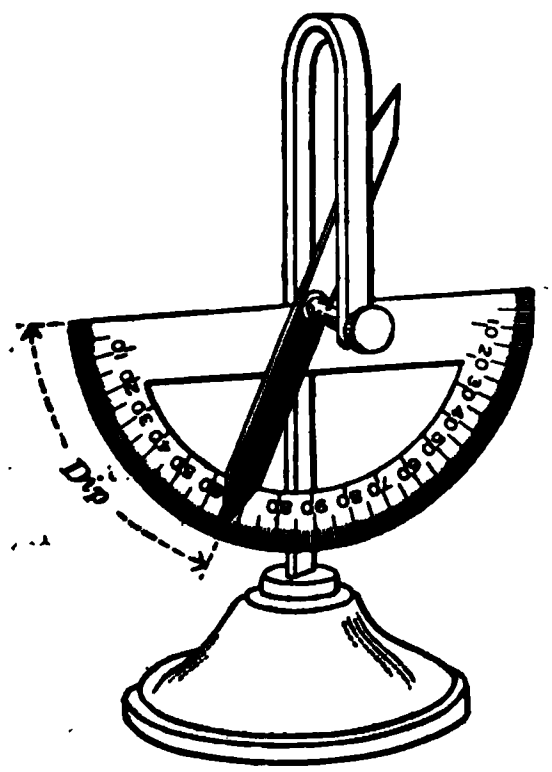

Fig. 277. Needle showing magnetic dip.

that in the extreme northeastern section of the United States the declination is as much as 20° W. This decreases to zero at a place near Columbus, O., and becomes an easterly declination amounting to 20° E. in the northwest.

It was nearly a hundred years after Columbus's time before it was discovered that if a compass needle is perfectly balanced so that it can swing up and down as well as sidewise, its north-seeking pole will dip down (Fig. 277) at a considerable angle in the

northern hemisphere. This angle increases as one goes farther north, and decreases as one goes south. Along a line near the equator there is no dip. In the southern hemisphere the north-seeking pole of a needle points up in the air, and Shackleton's South Polar Expedition found a point on the great Antarctic continent where a dipping needle would hang vertically with its north-seeking pole on top.

250. The earth a magnet. An Englishman, Gilbert, in the sixteenth century was the first to explain these curious magnetic phenomena. He had ground a little lodestone into the shape of a globe and noticed that when tiny compass needles were brought near it, they acted just like compasses on the surface of the earth. So he called his lodestone globe the "terrella," or "little earth," and came to believe that it gave a true representation of the earth itself.

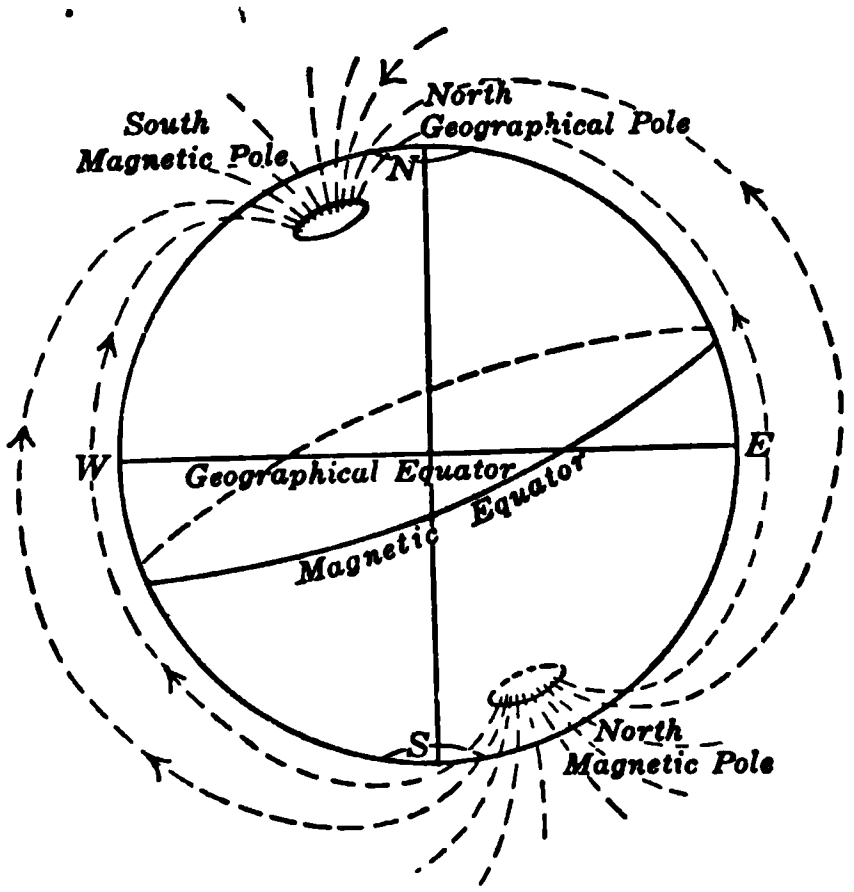

Fig. 278. The earth acts as a magnet.

The earth is, then, simply a huge magnet (Fig. 278), much thicker in proportion to its length than the magnets with which we are familiar in laboratories, but otherwise exactly like them. It has a north-seeking and a south-seeking pole like any other magnet; but from the laws of attraction and repulsion we see that, curiously enough, its south-seeking pole must be at Peary's end, and its north-seeking pole at Amundsen's end. These magnetic poles are not exactly at the geographical poles. One of them is in North America near Hudson's Bay and the other is nearly opposite in Antarctica near South Victoria Land.

Since the lines of equal declination and of equal dip are not true circles, the magnetization of the earth must be somewhat irregular. Furthermore, the positions of its magnetic poles are known to be changing slowly from year to year. Why these things are so, and, for that matter, why the earth is magnetized at all, is not yet known.

QUESTIONS

1. Does a magnet ever have more than two poles?

2. In what direction did Peary's compass point when he reached the North pole?

3. How far is the magnetic pole from the geographical North pole?

4. How can you tell whether or not a steel rod is a permanent magnet?

5. Why are knives, files, and scissors sometimes found to be magnetized?

6. Will a magnet attract a tin can? Explain.

7. Would a magnet floating on a cork in a dish of water float toward the north, as well as turn north and south? Give your reasons.

Fig. 279. Michael Faraday (1791–1867). Distinguished English physicist and chemist. Made important discoveries in electrochemistry and in electromagnetism.

8. How would you use a compass needle to determine the polarity of the end of a mass of iron?

9. How would you use a compass needle to compare roughly the pole-strengths of two magnets?

251. The field around a magnet. Michael Faraday (Fig. 279) was the first to see that a true understanding of the action of magnets could be had only by studying the empty space around them, as well as the magnets themselves.

One way to do this is to lay a stiff sheet of paper (or celluloid) over a magnet and sprinkle iron filings on it (Fig. 280). When the paper is tapped lightly so as to shake the filings about a little, they arrange themselves in regular lines leading from one pole to the other. This is because each filing gets slightly magnetized by the influence of the original magnet, and sets itself in the direction in which a tiny compass needle would lie if it were at the same place. This can be verified by

Fig. 280. Magnetic lines of force around a bar magnet traced by iron filings.

actually using a small compass instead of the filings. The lines can be mapped in this way, but it is not as quickly done.

In this way Faraday drew what he called **lines of force** around a magnet. *A line of magnetic force may be defined as a line which indicates at its every point the direction in which a north-seeking pole is urged by the attractions and repulsions of all the poles in the neighborhood.* When lines of force are thought of in this way, they should have little arrowheads on them, pointing in the direction of their journey from a north-seeking pole to a south-seeking pole. We shall find this conception of lines of magnetic force, or **magnetic flux**, a convenient way of remembering how a magnet will affect other magnets in its vicinity.

252. Lines of force like elastic fibers. Faraday himself thought of these lines of force as having a much more real

meaning than this. He thought of them as actually existing throughout the space around every magnet, even when there are no filings to show them. He believed that they represent a real state of strain in the ether (see section 190), in which all material bodies are immersed. Even now we know very little about what the ether really is. We know simply that it is not a kind of matter, but something much more subtle and fundamental.

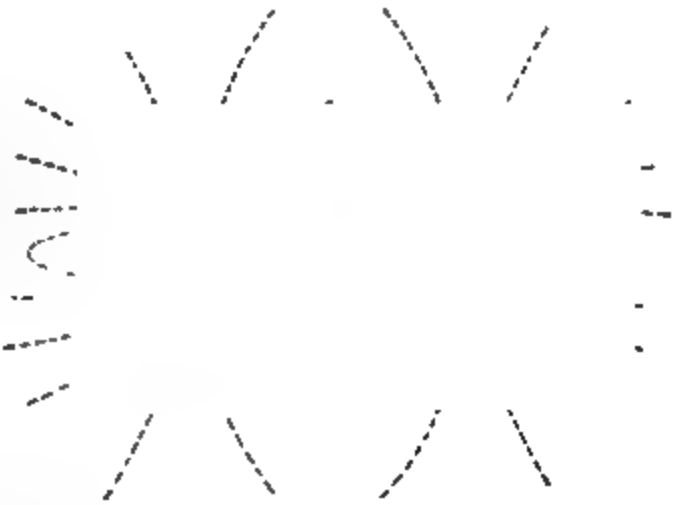

Fig. 281. Lines of force between two unlike poles.

At any rate, these lines of force of Faraday's *act as if they were stretched fibers in the ether* which are continually trying to contract and are thus pulling on the poles at their ends. They also *act as if they were trying to swell up sidewise as they contract*, and thus seem to crowd each other apart. It is not easy to see *why* lines of force have these properties; but once the properties are assumed (as rules of the game), it is easy to reason out from them *what will happen* in many practical cases.

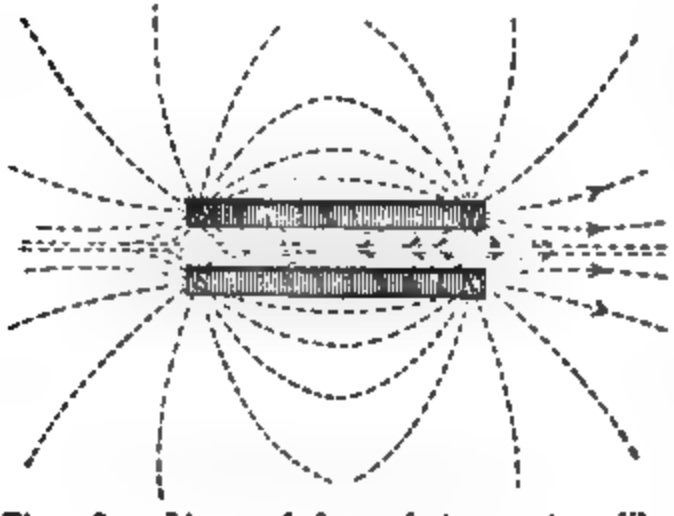

Fig. 282. Lines of force between two like poles.

If two magnets are placed with their *unlike* poles together and their lines of force traced with iron filings, the result will be as shown in figure 281. If we assume that the lines of force tend to contract, it is easy to see that two unlike poles must *attract* each other. But *like* poles would show a field of force as represented in figure 282;

if we assume that lines of force squeeze against each other sidewise, and tend to separate, evidently two like poles must *repel* each other. This is not an explanation of *why* these things happen; it is, however, an easy way of remembering *what* will happen, and it will be useful later on.

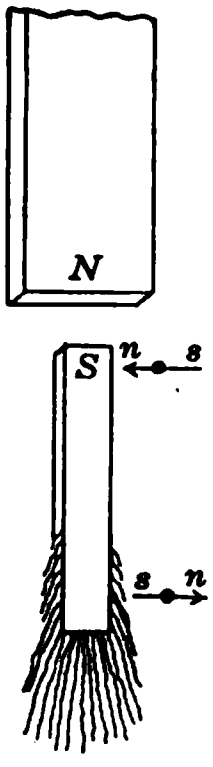

Fig. 283. A magnet by induction.

253. Induced magnetism. If we plunge one end of a piece of unmagnetized soft iron into some iron filings, it does not attract them; but if we bring near it a permanent magnet, as shown in figure 283, the soft iron becomes a magnet and attracts the filings. When the permanent magnet is removed, the soft iron loses its magnetism and drops the filings.

A piece of iron which is magnetized by being near a magnet is said to be **magnetized by induction.** If the pole of the magnet which was brought near the iron was a north-seeking pole, the induced magnet can be shown by a compass to have a *N*-pole away from the magnet and a *S*-pole near the magnet.

Experiments show that very soft iron quickly becomes magnetized by induction and quickly loses its magnetism when the field is removed. Hardened steel, however, is magnetized with difficulty, but retains its magnetism well. For this reason the magnets used in telephones and magnetos are made of hardened steel.

254. Permeability. If a piece of soft iron is placed in a magnetic field, it is found that all the lines of force in the vicinity tend to crowd into the iron.

Thus, figure 284 shows the field around the pole pieces of a permanent magnet, such as is used in a magneto, with a piece of soft iron shaped like the cross section of the armature between the poles of the magnet. A piece of wood or of brass would have almost no effect on the field.

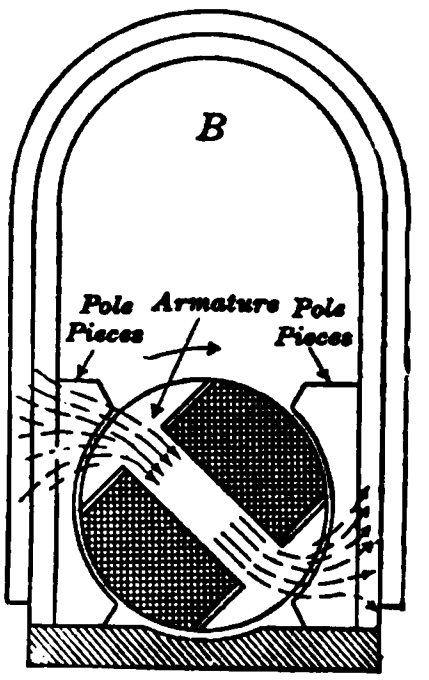

Fig. 284. Field about the poles of a magneto with soft-iron armature core between the poles.

Lord Kelvin called the ease with which lines of force may be established in any medium, as compared with a vacuum, the **permeability** of the medium. Thus iron has a permeability several hundred times greater than air. When a watch is brought near a powerful magnet, its balance wheel is often magnetized. This disturbs its working. To protect it from such magnetic disturbances a good watch is often shielded by being inclosed in a soft-iron case.

255. Uses of permanent magnets. Besides being used in mariners' and surveyors' compasses, magnets, as we shall learn in later chapters, are essential parts of various electrical measuring instruments, such as galvanometers, ammeters, voltmeters, and watt-hour meters. Every telephone receiver has a little permanent magnet inside its case. Every time a telephone bell rings, a permanent magnet has played its part in controlling the motion of the clapper; and on most rural lines the current with which one rings up "central" is generated with the help of several permanent magnets. Every Ford automobile has 16 permanent magnets bolted to its flywheel (Fig. 285); and every motor cycle and airplane carries permanent magnets in its **magneto**. Probably there are at least two hundred million permanent magnets in commercial use in this country at the present time.

Fig. 285. Sixteen horseshoe magnets bolted to the flywheel of a Ford engine.

In all these commercial applications of the permanent magnet the steel is bent more or less into a horseshoe shape, so that the two poles are brought close together, thereby greatly increasing the strength of the magnetic field. To get a magnet of constant strength, crucible tungsten steel is used, and after it has been shaped, hardened, and magnetized, it is **artificially**

aged. One way of doing this is to heat the magnet in a bath of boiling water or oil several times.

256. Theory of magnetism. Our present theory of magnetism is suggested by the following experiment.

Let us harden a knitting needle or a piece of watch spring by first heating it red hot and then plunging it into cold water. Then let us magnetize it and mark the *N*-pole. If we now break it near the middle where it does not show any magnetism, we find, by bringing the broken ends near a compass needle, that we have an *N*-pole and an *S*-pole

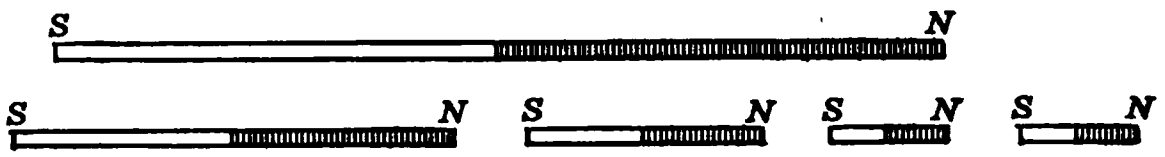

Fig. 286. A broken magnet shows poles at the break.

at the break. If we repeat the process, we find that each time the magnet is broken, new poles are formed, as indicated in figure 286.

A magnet can be broken into a great number of little magnets. A glass tube full of iron filings can be magnetized, but when shaken, it loses its magnetism. Any magnet loses a part or all of its power if it is heated red hot, jarred, hammered, or twisted.

All these facts point to a **molecular theory of magnetism,** which was suggested by a Frenchman, Ampère, and elaborated by a German, Weber, and an Englishman, Ewing. Every molecule of a bar of iron is supposed to be itself a tiny permanent magnet — why, no one yet knows. Ordinarily, these molecular magnets are turned helter-skelter throughout the bar (Fig. 287), and have no cumulative effect that can be noticed outside the bar. When the bar is magnetized, however, they get lined up more or less parallel (Fig. 288), like soldiers, all facing the same way. Near the middle of the bar the front ends of one row are neutralized by the back ends of the row in front; but at the ends of

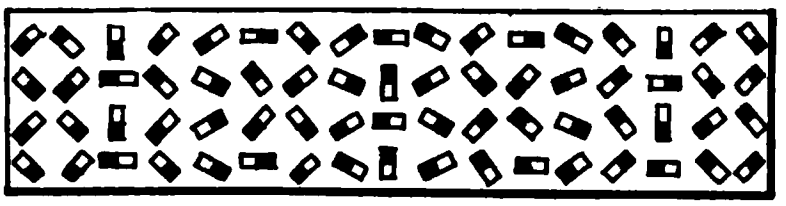

Fig. 287. Model of an unmagnetized bar.

the bar a lot of unneutralized poles are exposed, north-seeking at one end and south-seeking at the other. These free poles make up the active spots which we have called the poles of the magnet.

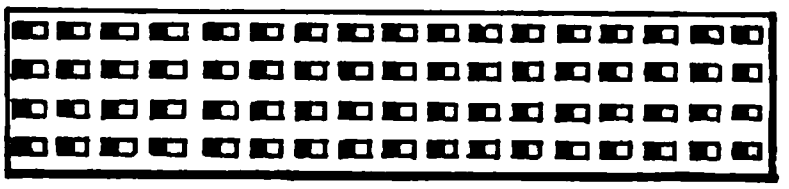

Fig. 288. Model of a magnetized bar.

On this theory it is easy to see that when a magnet is broken in two without disturbing the alignment of the molecular magnets, the new poles which appear at the break are simply collections of molecular poles that have been there all the time, but are now for the first time in an independent, recognizable position.

It will also be evident that, if this theory is true, there is a perfectly definite limit to the amount of magnetism a given piece of iron can have. For when all the molecular magnets are lined up in perfect order, there is nothing more that can be done, no matter how strong the magnetizing force may be. Such a magnet is said to be **saturated.**

SUMMARY OF PRINCIPLES IN CHAPTER XIII

Like poles repel each other.

Unlike poles attract each other.

The earth is a magnet with its south-seeking pole at Peary's end.

Lines of force tend to contract and swell sidewise; that is, there is tension along them, and compression at right angles to them.

QUESTIONS

1. If two bar magnets are to be kept side by side in a box, how should they be arranged? Why?

2. If a magnetic needle is attracted by a certain body, does that prove that the body is a permanent magnet?

3. How must a ship's compass box be supported so as to remain steady during the rolling of the ship?

4. One of the standard compasses used in the U. S. navy is called the "Liquid Type." Explain how it is constructed and its advantages.

5. A long soft-iron bar is standing upright. Why does its lower end repel the north pole of a compass needle?

6. Does hammering the bar while it is in the position described in question 5 increase or decrease the effect? Why?

7. Why are the hulls of most iron ships permanently magnetized? What determines the direction in which they are magnetized?

8. How can the compass on an iron ship be "compensated" for the induced magnetism in the ship?

9. The Carnegie Institute has a special ship built almost without iron. For what kind of survey of the world do you suppose it is made? What is the advantage of such a ship for this purpose?

10. How does a jeweler demagnetize a watch?

11. Recently a new compass has been developed which does not depend on magnetism. What is it called? Upon what principle does it work?

12. What additional information besides the direction of the compass is needed to determine the true north?

PRACTICAL EXERCISES

1. Making a magnet. Harden a steel knitting needle, an old file, or a piece of a clock spring by heating it red hot and then plunging it into cold water. It may be magnetized by stroking with a permanent magnet or, better still, by an electromagnet (see section 299). Mount on a sewing-needle point in a little box and use as a compass.

2. Photographing lines of magnetic force. In a dark room place over a magnet a piece of photographic printing paper (Velox), sensitized side up, so as to furnish a flat, horizontal surface. Sprinkle iron filings on the paper. Turn on an electric lamp directly above for a few seconds, or light two or three matches. Shake off the filings and develop the paper. Compare your picture with figure 280. Repeat with two or more magnets variously arranged, and also with an unmagnetized piece of soft iron near a magnet.

CHAPTER XIV

STATIC ELECTRICITY

Electricity by friction — conductors and insulators — positive and negative charges — electroscope — distribution of electricity — charging by induction — condenser — electrophorus — atmospheric electricity — electron theory of electricity.

257. Electricity by friction. As far back as 600 B.C., Thales, a Greek, knew that amber, when rubbed, would attract bits of paper or other light objects. We now know that many other substances, such as rubber, glass, and sulfur, have the same property. Anyone can observe this on a cold, dry morning after combing his hair vigorously with a hard-rubber comb. The comb will then support long chains of bits of paper. Since amber, in common with gold and certain bright alloys, was called " electron " by the Greeks, these phenomena were many years later named by Gilbert **electric** phenomena.

Objects which have gained this property of attracting small bits of paper are said to be **electrified**, or to have an **electric charge.** Any object which has not been charged is said to be **neutral.** By many careful experiments it has been found that *any two different substances when rubbed together, or even brought into close contact, become somewhat electrified.*

258. Electric *vs.* magnetic attraction. These electric attractions are in many ways so much like magnetic attractions that it was not until the sixteenth century that it was clearly seen that two very different kinds of phenomena are involved. *Magnetization* can be produced only in three metals, iron, nickel, and cobalt, and in one or two uncommon alloys; while *electrification* can be produced by rubbing almost any substance, especially a non-metal. A magnetized body always has at

least two poles where its magnetism is more or less concentrated; and these poles are *unlike*, for if one of them attracts the north-seeking end of a compass, the other will always repel it. A metallic body electrified by friction will ordinarily not have its properties concentrated in spots, and all parts of it will act very much *alike* in their attracting power. Nevertheless, we shall presently see that there are two kinds of electricity, just as there are two kinds of magnetic poles.

259. Conductors and insulators. Some substances will conduct electricity, while others will not. Thus a metal sphere can be charged with electricity by touching it with some electrified substance, such as a stick of sealing wax which has been rubbed with a cat's skin, *if* the sphere is suspended by a dry silk thread, but *not* if suspended by a wire. In the latter case just as much electricity gets into the sphere as in the former, but it all runs out again through the wire. Similarly an electrified body loses its charge if touched by any part of the experimenter's body. *Substances which lead off the electric charge quickly, such as metals, are called* ***conductors****; those which prevent the charge from escaping, such as amber or dry silk, are called* ***nonconductors*** *or* ***insulators***. It is to prevent the leakage of electricity from the conductor that electric-light, telephone, and telegraph wires are supported on glass or porcelain knobs, called "insulators."

There is no sharp line between conductors and insulators; most substances conduct a little, and even the good conductors vary greatly in conductivity.

In the following table a few other common substances are arranged according to their insulating powers.

Insulators	Poor Conductors	Good Conductors
Hard rubber	Dry wood	Metals
Dry air	Paper	Gas carbon
Paraffin	Alcohol	Graphite
Sulfur	Kerosene	Water solutions of
Resin	Pure water	salts and acids

It will be noticed that the substances which can be easily electrified by friction are all insulators. One reason for this is that when electricity is generated at any point on an insulating body by rubbing, it stays there and makes its presence known; but if the body is a conductor, the electricity leaks away at once.

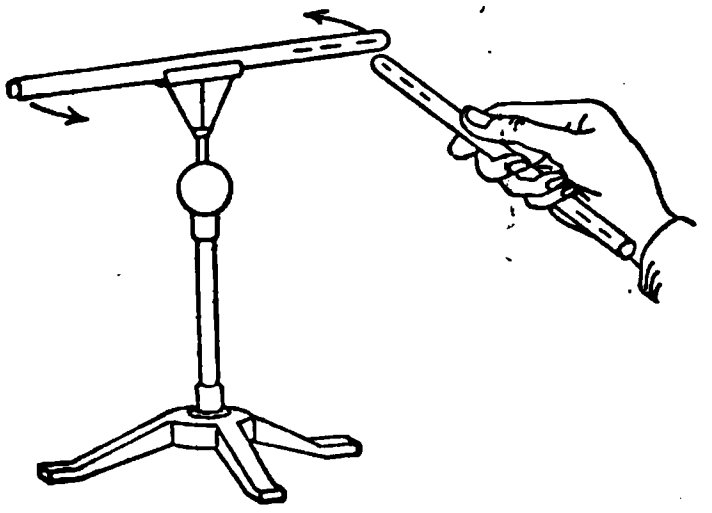

Fig. 289. Two electrified rods with like charges repel each other.

Those substances which are good conductors of electricity are also good conductors of heat. This curious phenomenon seems to be due to the fact that both heat and electricity are carried through metals by a swarm of tiny particles, called **electrons**, which drift about between the much larger molecules of metal.

260. Positive and negative electricity. If we hang up in a stirrup, suspended by a silk thread (or balance on a needle point, supported by an insulator) a glass rod which has been rubbed with silk, and then bring near one end of it another glass rod which has also been rubbed, they repel each other (Fig. 289). In a similar way, two hard-rubber rods or sticks of sealing wax rubbed with catskin or flannel repel each other. But when we bring a rubbed stick of sealing wax near a rubbed glass rod in the stirrup, they attract each other.

Such experiments show that there are two kinds of electrification. By universal consent scientific people have agreed to call that *kind of electrification which appears on glass when rubbed with silk* ***positive***; and that *kind which appears on sealing wax or hard rubber when rubbed with flannel* ***negative***. Bodies charged with the same kind of electricity repel each other, and bodies charged with different kinds of electricity attract each other. That is,

Like charges repel and unlike charges attract.

Experiments also show that an *electrified body*, whether it is positively or negatively charged, *attracts an unelectrified body*.

261. How to detect electricity. To test the electrical condition of a body we use an **electroscope.** A simple form of electroscope consists of a pith ball hung by a silk thread from a glass support (Fig. 290).

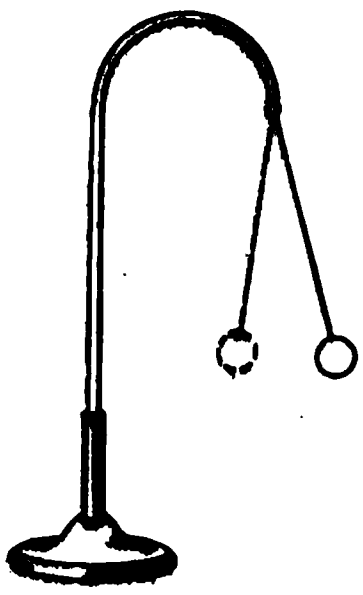

Fig. 290. Pith-ball electroscope.

If an uncharged body is brought near the pith ball, nothing happens. If a positively charged body is brought near the pith ball, the latter is attracted, becomes itself positively charged, and is then repelled. Then if a negatively charged body is brought near, the positively charged pith ball is attracted, but when it touches, it becomes negatively charged and flies back. If we now bring a negatively charged body near, the negatively charged pith ball is repelled. If, then, we know what the nature of the charge on the pith ball is, and find that a body repels it, we know the body must be charged the same way.

A more reliable form of electroscope is the so-called "gold-leaf" **electroscope,** although nowadays it is quite commonly made of an aluminum leaf hung beside a brass strip. The instrument is usually mounted in some sort of glass case, as shown in figure 291, to protect it from air currents.

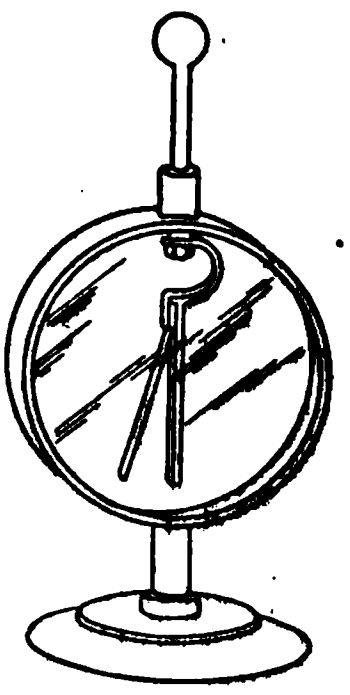

Fig. 291. Aluminum-leaf electroscope.

When one brings near the top of the brass rod a charged glass rod, the aluminum leaf swings out from the brass strip. If the rod is removed, the leaf falls down again. If, however, one actually touches the charged rod to the electroscope, the leaf swings out and stays there.

The electroscope is then said to be charged positively. If we bring near a positively charged electroscope a positively charged body, the leaf will fly farther out; but if the body brought near has a negative charge, the leaf will swing down. In either case it will return to its original charged position when the outside charged body is taken away. Thus with an electroscope carrying a known charge one can tell the electrical condition of a body.

With such an electroscope it is possible to learn much about electrified bodies. For example, when an insulated conductor is rubbed, it becomes charged with electricity; so we conclude that all bodies become electrified by friction. If we stand on an insulated stool while we rub a glass rod, our body becomes negatively charged; and by rubbing sealing wax with cat's fur, we become positively charged. In general, *whenever two different substances are rubbed on one another, one becomes positively charged with electricity, while at the same time the other is negatively charged.*

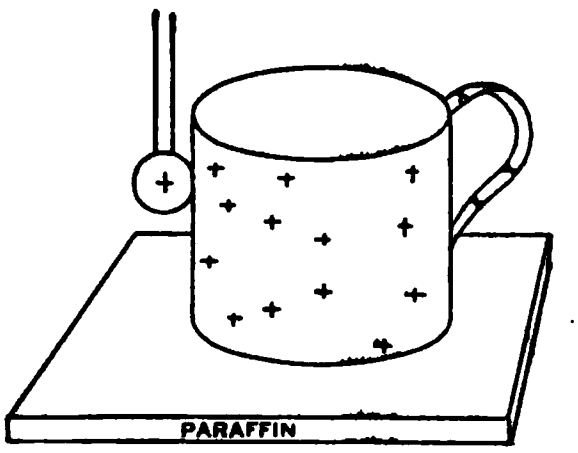

Fig. 292. Charging an insulated tin cup.

262. Distribution of electricity on a conductor. Let us place a tin cup on a cake of paraffin, as shown in figure 292, and charge it as much as possible either positively or negatively. We can then test it at various points by means of a little metal disk or ball mounted on an insulating handle and known as a **proof plane.** If we touch the outside surface of the charged cup with the proof plane and then bring the latter near the knob of a charged electroscope, we find that there is a strong charge on the outside of the cup. If we touch the inside surface, we find no charge at all.

That is, *the charge is entirely on the outer surface of a conductor.* It can also be shown that its greatest density is at the corners and projecting points. In fact, the density of the charge at sharp points is so great that it will escape into the air easily at such points.

QUESTIONS

1. Compare the behavior of a magnetic pole with the behavior of an electrically charged body.

2. Does a freely swinging charged body take a definite direction?

3. What becomes of the mechanical energy exerted in rubbing a glass rod to electrify it?

4. What kind of electricity is generated by rubbing a stick of sulfur on woolen cloth?

5. Why do experiments with frictional electricity work better on a cold, dry, winter day?

6. Does one remove magnetism from a magnet by touching it with iron?

7. Faraday built a large box and lined it with tin foil. He then took his most sensitive electroscope into the box and found that even when the outside of the tin foil was so charged that it sent forth long sparks, he could not observe any electrical effects inside. Explain.

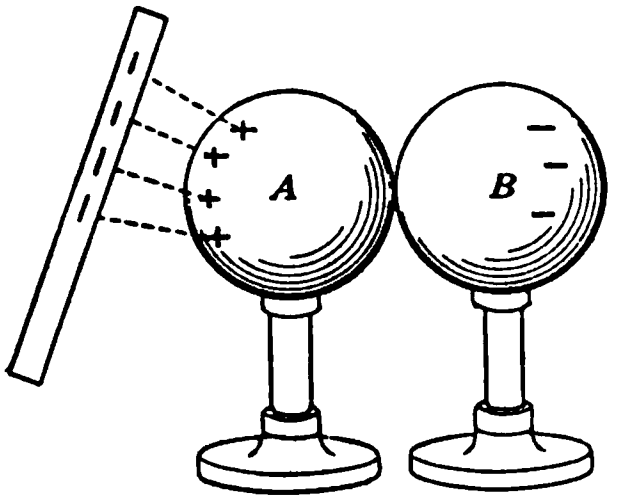

Fig. 293. Charging two metal spheres.

8. In testing the electrification of a body with a charged pith ball suspended by a silk thread, would attraction or repulsion be the better test? Why?

9. Which are more important in their commercial applications, conductors or insulators? Give your reasons.

263. Charging by induction. We have already seen that it is possible to influence an uncharged electroscope by bringing near it an electrified body; but we have also seen that this influence disappears as soon as the charged body is removed. This *method of producing a temporary electrification by the presence of a charged body in the neighborhood is called* ***charging by induction.***

Let us illustrate this process of electrification by placing two metal balls A and B on insulators side by side, as shown in figure 293. We now bring a negatively charged body, such as a rubbed stick of sealing wax, near the ball A, which touches ball B, and while the charged body remains near A, we separate the balls. On testing the balls we find that A is positively charged and B is negatively charged.

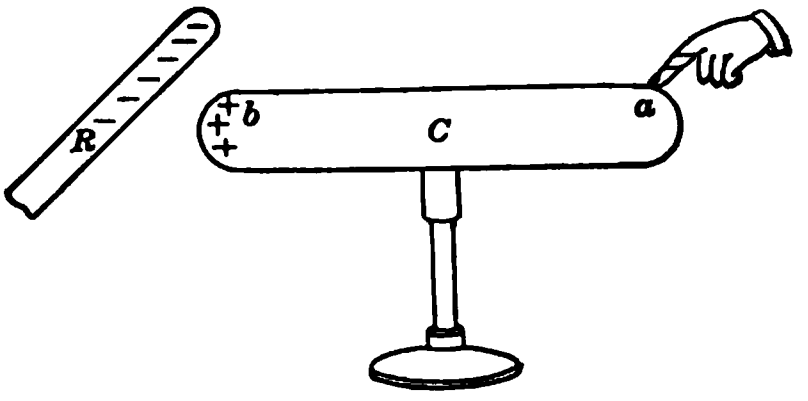

Fig. 294. Charging a conductor by induction.

If a conductor C is touched at a by the finger while a negatively charged rod R is held near it, as shown in figure 294, and if the finger

is *first* removed and *then* the charged rod, we find that the conductor has become charged positively. If we repeat the experiment but this time touch the conductor at some other point, such as *b*, we find that the conductor is charged positively exactly as before.

We may explain this process of charging by induction as follows. When the negatively charged rod is brought near an insulated conductor, the positive and negative electricity in the conductor are distributed so that *the remoter part has a charge of the same kind as the inducing charge and the nearer part has a charge of the opposite kind.* If we cut the conductor in two while it is under the influence of an electric charge, we obtain two permanently charged bodies. If we touch the conductor, the negative electricity, which is repelled, finds its way to the ground through our body, but the positive electricity remains **bound.** In general, we conclude that *in charging by induction the sign of the charge induced is opposite to that of the inducing charge.*

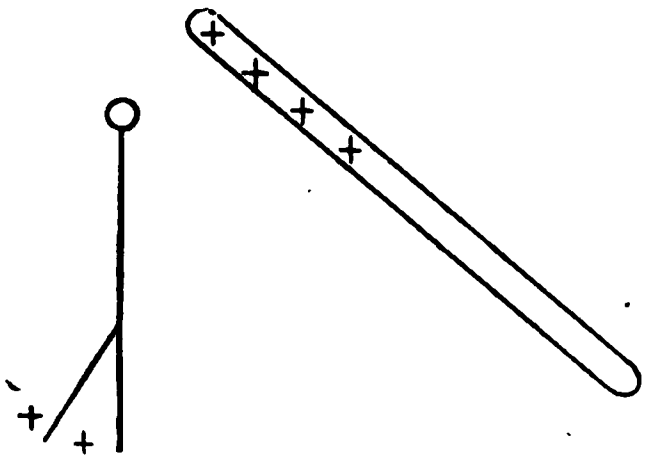

Fig. 295. Charging an aluminum-leaf electroscope by induction.

This helps us to understand the gold-leaf electroscope. When a charged body is brought near the knob of the electroscope, the leaf swings out because it and the strip are charged by induction with the same kind of electricity as the charged body (Fig. 295). If the electroscope is charged by contact positively and a positively charged body is brought near, it repels more of the positive electricity into the leaf and it swings out farther. On the other hand, if a negatively charged body is brought near, it draws some of the positive electricity up into the knob, and the leaf drops somewhat.

264. Condenser. In many practical applications of electricity it has been found necessary to increase the capacity of a conductor for holding electricity. This is done in what is called a condenser.

Let us arrange a metal plate on an insulating base and connect the plate by a wire to an electroscope, as shown in figure 296. If we charge the plate *A*, we see the leaf of the electroscope swing out. We now bring up a second metal plate *B* similar to plate *A*, but connected with the ground. As we bring plate *B* near plate *A*, the electroscope leaf begins to fall, but if we remove plate *B* again, the leaf swings out as before.

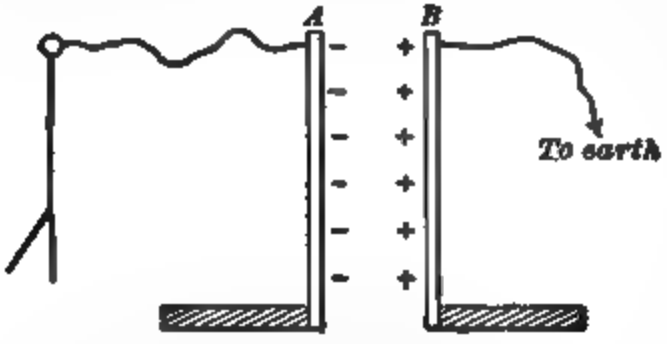

Fig. 296. Action of a condenser.

Let us now bring the plate *B* back to a position near plate *A*, and charge plate *A* until it shows the same deflection as before. It will be evident that the capacity of plate *A* for holding electricity is much increased by being close to a similar grounded plate *B*.

We may also show the influence of an insulating material between the conducting plates by introducing a pane of glass. The leaf of the electroscope falls, but rises again when the glass is removed. This shows that the capacity of the condenser is increased by the glass plate.

A combination of conducting plates separated by an insulator is called a condenser. The capacity of a condenser for holding electricity is proportional to the size of the plates and increases as the distance between them decreases. It also depends on the nature of the insulator, or dielectric, as it is called, being much greater when glass, mica, or paraffin paper is used than when a layer of air is the dielectric.

265. Commercial condensers. As early as 1745, someone at the University of Leyden in Holland made a condenser out of a wide jar or bottle (Fig. 297) by coating it inside and out with tin foil. This so-called **Leyden jar** is still employed in experimental work. But the condensers used in telephones, induction coils, and

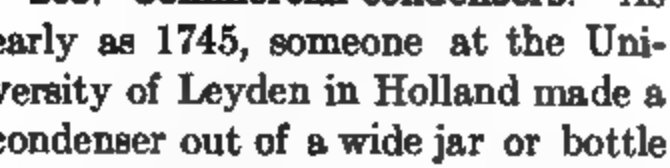

Fig. 297. Condenser made in the form of a Leyden jar.

radio telegraphy generally have a much more compact form. Figure 298 shows two sets of interlaid layers of tin foil separated by sheets of paper coated with paraffin, or by sheets of mica. The alternate layers of tin foil are connected to each other and form two terminals, as shown in figure 299. There is no electrical connection between the condenser terminals, and so one set of tin-foil sheets may be charged positively while at the same time the other set is charged negatively. These positive and negative charges hold or bind each other so that a large quantity of electricity may be accumulated. The capacity of such a condenser is proportional to the area of the plates and to the number in each set.

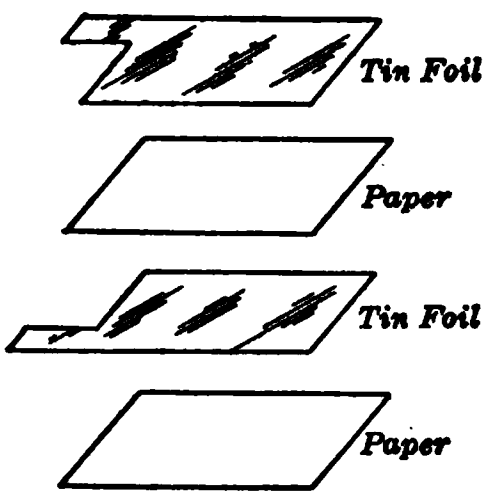

Fig. 298. Construction of a plate condenser.

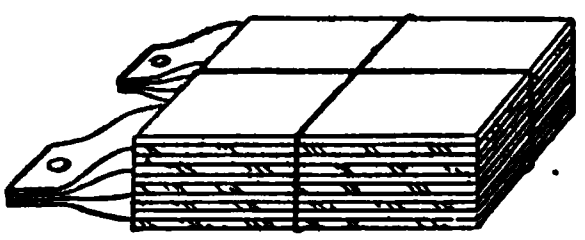

Fig. 299. Assembled plates of a condenser.

266. Hydraulic analogy of a condenser. We may illustrate a condenser by two standpipes filled to different levels with water, as shown in figure 300. The coatings of the condenser correspond to the standpipes. The pipe *A*, with the water standing at a higher level, represents the positively charged plate or coating, while the other pipe *B* is the negatively charged plate. The connecting pipe at the bottom of the tanks corresponds to the wire connecting the coatings. When the connection is made, the water rushes through the pipe and equalizes the levels very quickly. This represents the discharge of the condenser. When the valve *V* in the pipe is first opened, the water rushes through so fast that it usually overdoes things, and rises to a higher level in *B* than in *A*. Then it flows back again, and so on, oscillating back and forth until the

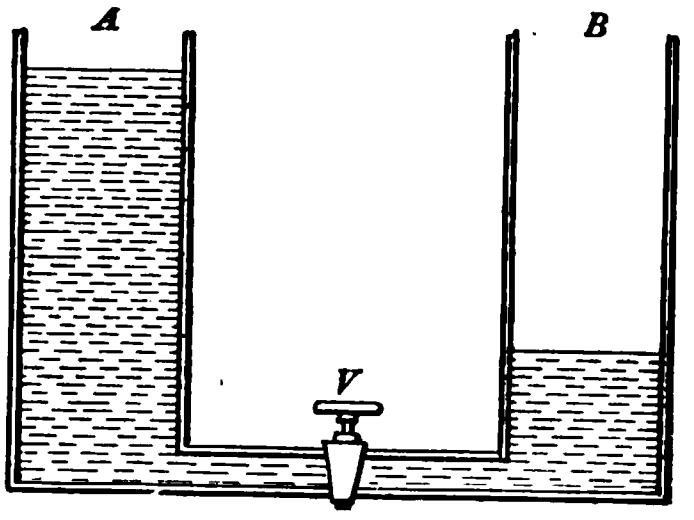

Fig. 300. Hydraulic analogy of a condenser.

motion dies out because of friction in the pipe. In much the same way, when a condenser is short-circuited, the discharge of electricity goes too far and charges the condenser the other way. Then it discharges back again, and so the electric charges oscillate very quickly back and forth until the motion of the electricity dies out because of something akin to friction, called the **electrical resistance** of the wire. The technical way of describing this is to say that the discharge of a condenser is **oscillatory**.

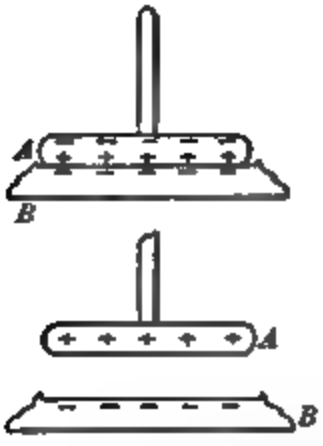

Fig. 301. Electrophorus.

267. Induction machines for producing electricity. The simplest machine for producing electricity by induction is the **electrophorus**. It consists of a hard-rubber plate and a somewhat smaller metal disk with an insulating handle.

The hard-rubber plate (*B* in Fig. 301) is rubbed with cat's fur, which charges it negatively. We then place the metal disk *A* on the plate and touch the metal disk so as to "ground" it. When we lift the disk and bring it near the knob of a Leyden jar, a spark jumps across the gap. A Leyden jar can be strongly charged with an electrophorus by repeating this process again and again.

When the metal disk is placed on the negatively charged plate, a positive charge is attracted to the lower surface of the disk next to the plate, while the negative electricity is repelled. When we touch the metal disk, this negative electricity escapes through the hand to the ground. By this process the disk becomes positively charged throughout. After the rubber plate is once charged, any number of charges can be obtained from the electrophorus without producing any appreciable change in the charge on the plate. This is because the energy comes from the muscle that lifts the disk.

There are more complicated electrostatic machines, such as the Toepler-Holz and Wimhurst machines, which also make use of the principle of induction. These machines are chiefly used for lecture-table demonstrations.

268. Atmospheric electricity. It was about the middle

of the eighteenth century that Benjamin Franklin (Fig. 302) demonstrated by his famous kite that thunderclouds carry ordinary electrical charges and that *lightning is a huge electrical discharge, or spark.* This discovery was recognized as epoch-making by scientific men everywhere. Perhaps the most wonderful part of it was that Franklin was not killed at once, for within a year a man in Petrograd lost his life while performing a similar experiment.

Franklin then invented the lightning rod to conduct safely any electricity that might otherwise be discharged through a building by a stroke of lightning. When a charged cloud acts inductively on the earth, a bound charge of opposite sign is concentrated in good conductors and outstanding objects, such as trees and church steeples (Fig. 303), and we have a sort of huge condenser. If the charges become too great, or the cloud comes too near the earth, the intervening dielectric (the air) breaks down and the condenser discharges, producing a flash of lightning, which is sometimes five miles long, and a loud noise called thunder. The sound is thought to be caused by a sudden and violent expansion of the ribbon of air that is heated by the discharge.

Fig. 302 Benjamin Franklin (1706–1790). Famous American statesman, scientist, and author. Made a scientific study of electricity and invented the lightning rod.

Fig. 303. A charged cloud induces an opposite charge in church steeples.

Until recently the **cause of the electrification** of thunderclouds has been a mystery. It has now been shown experimentally that when water falls through an upward current of air, violent enough to produce spray, the larger of the resulting drops are usually positively electrified, while the finer mist carries a negative charge. Since thunderclouds form at the tops of huge upward currents of air, it is clear why the heavy rain of a thunderstorm is usually positively charged, and why the mist which is swept upward by the air current forms negatively charged clouds.

The effectiveness of the **protection against lightning** afforded by lightning rods is a subject on which there is much difference of opinion. It is certain that flimsy rods, poorly erected or not well grounded, are worse than no rods at all. On the other hand, several substantial conductors starting from well-distributed points on a roof or from the top of a steeple and leading *without sharp bends* and *always downward* to *good grounds* doubtless afford valuable protection. Telephone and electric-light wires and electric-power lines are commonly protected by various kinds of lightning arresters.

269. The electron theory of electricity. We now believe that all substances are composed of one or more simple substances called **elements**. Water, for example, is composed of the elements oxygen and hydrogen. We define *an atom as the smallest particle of an element which can take part in chemical change.* We have already seen that a gas is composed of a vast number of minute particles called **molecules**. In most common gases, such as oxygen, nitrogen, and hydrogen, each molecule is made of two atoms held together in chemical combination. In a compound a molecule is composed of two or more atoms of *different* elements. Thus a water molecule is composed of 2 atoms of hydrogen and 1 atom of oxygen.

The atoms of all elements are believed to contain as constituents both positive and negative electricity. The negative electricity exists in the form of very minute corpuscles, or **electrons**, which are grouped in some way about the positive electricity as a nucleus. Although the hydrogen atom is the

lightest atom known and is much too small for us to hope ever to see it, even with the most powerful microscope, yet each electron has a mass $\frac{1}{1845}$ of that of the hydrogen atom.

A *negatively* charged body is one which contains *more* electrons than its normal number; a *positively* charged body is one which contains *less* electrons than its normal number. In a conductor the electrons are continually getting loose from the atoms and reëntering other atoms; and so at any given instant there are in a conductor a great number of *free* electrons and a corresponding number of atoms which have lost electrons and so are positively charged. The larger the number of free electrons in any substance, the greater the conductivity of that substance. An insulator is a substance which contains no free electrons.

The process of charging by induction is very simply explained by the electron theory. When a positively charged body is brought near an insulated conductor, the free electrons in the conductor are attracted from all parts of the conductor to the end nearest the positively charged body. Hence that end is negatively charged. Since these electrons were drawn away from the far end of the conductor, it has less than its normal number of electrons and is therefore positively charged.

SUMMARY OF PRINCIPLES IN CHAPTER XIV

All bodies can be electrified by *friction*, becoming charged either positively (vitreously) or negatively (resinously).

Like charges repel each other.

Unlike charges attract each other.

All conductors can be electrified by *induction*, showing both a positive and a negative charge in different places. Of these, one is *bound* by the inducing charge, but the other is *free*.

QUESTIONS

1. Why cannot a Leyden jar be appreciably charged if the jar stands on a cake of paraffin?

2. If a charged Leyden jar is placed on a cake of paraffin, why does one not get a shock if one touches the knob?

3. How would you with safety discharge a condenser?

4. Why does a brick chimney need a lightning rod more than a steel smokestack of the same height?

5. If an insulated metal globe is negatively charged, how can any number of other insulated metal globes be positively charged? Does the first globe lose any of its charge?

6. If an insulated metal globe is negatively charged, how can any number of other insulated metal globes be negatively charged? Does the first globe lose any of its charge?

7. In charging an electroscope by induction, why must the finger be removed before the removal of the charged body?

8. Explain how the electrophorus illustrates the transformation of mechanical into electrical energy.

9. Describe the action of an electrophorus according to the electron theory.

PRACTICAL EXERCISE

Different forms of condensers. Find out how the condensers in automobile spark coils differ in construction from those used in radio telegraphy. Why?

CHAPTER XV

ELECTRIC CURRENTS

Electricity in motion — water currents — electric cell — electric circuit — ampere, ohm, and volt — hydraulic analogy — Ohm's law — measurement of current, voltage, and resistance — computation of resistance — wire table — temperature effect on resistance — series circuits — Ohm's law applied to partial circuits — parallel circuits — cells in series and in parallel — construction of a dry cell — its defects — terminal voltage — voltage drop in a line.

270. Electricity at rest and in motion. Until the nineteenth century practically all that people knew about electricity dealt with **electricity at rest** (electrostatics). Almost the only useful invention was the lightning rod, and its value was much overestimated. The most useful instrument which had been devised was the condenser.

In the last fifty years, as we shall see in the next three chapters, electricity has suddenly leaped into a commanding position in the arts and in engineering. The telephone, electric light and electric motor, trolley cars, radio telegraphy, and electric transmission of power have become everyday affairs. All these involve **electricity in motion**, that is, electric currents.

271. Electric currents and water currents. Although the exact nature of electricity, which makes itself evident in so many ways, has never been determined, we can become familiar with the laws governing the effects and the applications of electric currents. We shall find it very useful to remember that we are dealing with something flowing along a conductor very much as water flows through a pipe.

For example, suppose a water tank is mounted beside a railroad track for filling the tank of a locomotive tender, as

shown in figure 304. We know that the water will flow from the tank through the pipe out into the tender. The water flows

Fig. 304. Difference of level tends to make water flow.

"downhill"; that is, it moves because a difference in level furnishes a motive force called hydraulic head. This head is measured by the difference of level between the water surface in the tank and the end of the pipe.

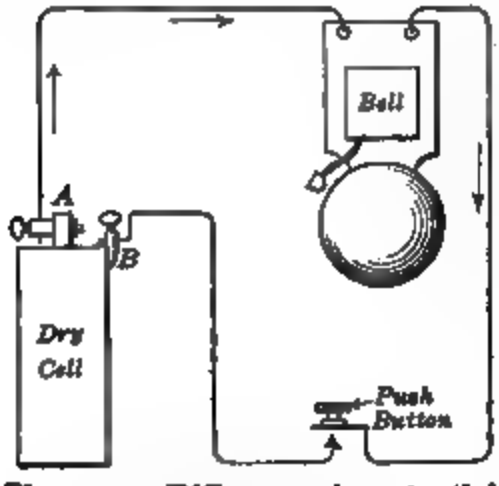

Fig. 305. Difference in potential in the dry cell causes electricity to flow along the wire.

In much the same way, if we connect the binding posts, or terminals, of a dry cell with a metal wire, a difference in the electrical condition of the two terminals causes an electric current to flow along the wire. The fact that the wire gets hot and that a bell rings when the button is pushed (Fig. 305) suggests that something is flowing along the wire. This we

call electricity. We describe the difference of electrical condition in the terminals of the dry cell as a difference of electrical potential, which tends to make electricity flow.

272. A simple electric cell. This method of setting up a difference of electrical potential and of maintaining an electric current by chemical action was discovered a little more than a hundred years ago by an Italian scientist, named Volta (Fig. 306).

Fig. 306. Alessandro Volta (1745–1827). Italian physicist who invented the electric battery, the electroscope, the electrophorus, and the condenser.

Suppose we place a strip of copper and a strip of zinc in a tumbler so that they do not touch each other and then pour in some dilute sulfuric acid (Fig. 307). We observe that the copper plate is not affected by the acid, while the zinc plate is soon covered with bubbles, which rise to the top, the zinc plate being gradually eaten away.

Careful experiments with a sensitive electroscope show that the *copper plate is positively charged* and the *zinc plate is negatively charged*. If we connect the plates by a wire containing an electric bell and push button, an electric current will flow through this wire from one plate to the other, as is indicated by the ringing of the bell. It is assumed that *the current flows in the wire from the copper* (the plate of higher potential) *to the zinc* (the plate of lower potential).

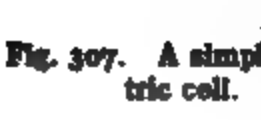

Fig. 307. A simple electric cell.

Almost any two electrical conductors might be used for the plates instead of zinc and copper; but the two plates must not be of the same material. Likewise, other liquids might be used in place of the sulfuric acid, but it is necessary that the liquid (called the **electrolyte**) should attack one of the metals chemically. It is customary to call the plate which is attacked the less readily the **positive (+) electrode**, and the other, the **negative (−) electrode.**

273. An electric circuit. *A current of electricity will not flow unless there is a* ***complete*** *conducting path or ring.* Such a path through which the current flows is called an **electric circuit.** That portion of the circuit which is outside the cell, including the electric bell, push button, and connecting wires, is called the **external** circuit; that part which is inside the cell itself, namely, the plates and the liquid, is called the **internal** circuit. It will be noted that the current in the external circuit flows from the copper (or carbon) to the zinc through the metal wires, and that its path is completed by the internal circuit from the zinc to the copper (or carbon) through the liquid. If we cut the wire outside the liquid, that is, **break the circuit,** the difference of potential will still remain, but no current can then flow because the conducting path is broken. If we again join the ends of the wire, that is, **make** or **close the circuit,** the current again flows.

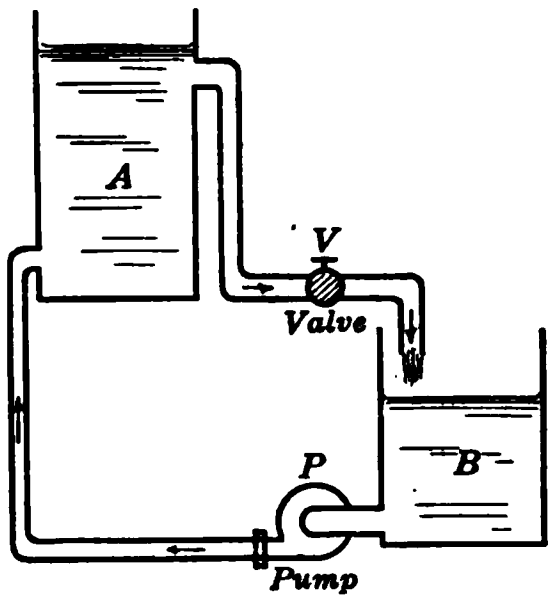

Fig. 308. Hydraulic analogue of a voltaic cell.

274. Hydraulic analogy. The action of a simple electric cell like that just described may be compared to a pump for circulating water through a system of pipes. *A cell may be considered as a machine for pumping electricity.*

Suppose two deep tanks, *A* and *B* in figure 308, are placed so that *A* stands on a higher level than *B*. A pipe with a pump *P* leads from

the bottom of *B* to the bottom of *A*. If the tanks are partly full of water and the pump is started, water will be drawn from the tank *B* into the tank *A*, thus raising the water level in the latter. If an overflow pipe is carried from tank *A* to tank *B*, the overflow will run back into the depleted tank, and the water will simply be circulated by the pump in a current flowing through the system of pipes and the two tanks. This is somewhat like the electric cell when the external circuit is closed.

Now if the overflow pipe is closed by a valve *V*, the pump will soon empty the tank *B*; after this it may continue to run, but it cannot pump any water, and no current of water will flow through the pipes.

This is similar to the condition in an electric cell which does not have its terminals connected by a wire. The plates will be maintained at a difference of electrical potential, but no current flows.

275. Unit of current. The ampere. The rate of a current of water flowing through a pipe may be expressed as a certain number of gallons or cubic feet per second. In the same way the rate of a current of electricity may be expressed as a certain quantity of electricity flowing per second past a certain point. The unit of quantity of electricity is called a **coulomb** in honor of the French scientist, Coulomb. The methods by which such a quantity of electricity may be measured are explained in section 324. *An electric current carrying one coulomb per second is called a current of* ***one ampere.*** This unit was named after the French physicist, Ampère (Fig. 309). Since we are usually interested in the rate of flow of

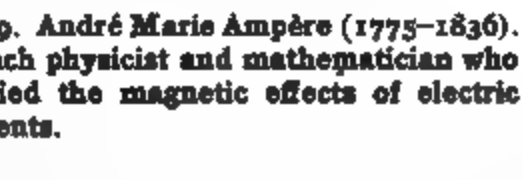

Fig. 309. André Marie Ampère (1775–1836). French physicist and mathematician who studied the magnetic effects of electric currents.

electricity and not the quantity, we use the term ampere very often and only rarely the term coulomb.

Thus, a new dry cell whose terminals are connected by a short stout wire causes about 20 amperes to flow through the wire. A 40-watt tungsten lamp takes about one third of an ampere, while the arc lamps used for street lighting require from 5 to 10 amperes. A telephone receiver operates on less than 0.1 amperes, while the motor on a street car often takes 40 or 50 amperes, and the starting motor of an automobile as much as 150 or 200 amperes.

276. Unit of resistance. The ohm. We are familiar with the fact that a stream of water flowing through a pipe is retarded by the friction of the pipe. If the pipe is long and small and rough, we know that it offers a large resistance to the flow of water through it. In a similar way *electrical resistance is the opposition which is offered by electrical conductors to the flow of current.* We have already (section 259) divided substances into two classes, conductors and nonconductors, or insulators; but even the best conductors of electricity are not perfect. All conductors offer some **resistance** to the flow of electricity.

The unit of resistance is the **ohm**, which is named after the German scientist, Dr. Ohm, who first set forth the law in regard to electric currents, which will be discussed in section 279.

Thus, 1000 feet of No. 10 copper wire has a resistance of almost precisely 1 ohm. About 157 feet of No. 18 copper wire (the size ordinarily used to connect electric bells) or 26 feet of iron wire or 6 feet of manganin wire of the same size has a resistance of 1 ohm. A $2\frac{1}{2}$-inch vibrating bell will usually have a resistance somewhere between 1.5 and 3 ohms, a telegraph sounder about 4 ohms, a telephone receiver 60 ohms, and a 40-watt Mazda lamp, when hot, 300 ohms.

277. Difference of potential. The volt. In hydraulics we know that in order to get water to flow along a pipe it is essential to have some driving force, due to a difference in water level, or to a pump. In much the same way, to get electricity to flow along a wire we must have an **electromotive force**, such

as that furnished by the difference of potential of an electric cell or by some other electric generator. The unit of electromotive force is called the **volt**, after the Italian scientist, Volta, who discovered the chemical means for producing electric current. *A volt may be defined as the electromotive force needed to drive a current of one ampere through a resistance of one ohm.*

For example, the electromotive force of a simple cell made of zinc and copper plates and dilute sulfuric acid is about one volt. A common dry cell gives about 1.5 volts, and a storage cell about 2 volts. The current for lighting a building is usually delivered at 110 or 220 volts, and street cars operate on about 500 volts.

Electromotive force (abbreviated e.m.f.) is sometimes called **voltage** or **difference of potential**. All of these terms mean the same thing, namely, the "push" that moves or tends to move electricity.

278. Distinction between volts and amperes. The intensity of an electric current is measured in **amperes**; the electromotive force driving the current is measured in **volts**. In a given circuit the greater the electromotive force is, the greater is the current. Just as we must have a certain "head" of water in order to get a given number of gallons of water to flow through a given pipe per second; so we must have a certain electromotive force in order to make a given current of electricity flow through a given wire. With both water and electricity we must have a motive force in order to have a current; but we may have the motive force and yet have no current. Just as when the valve is closed in a water pipe, if the switch is open in the electric circuit, we may have motive force (volts) but no current (amperes).

Since in our study of electricity we shall have very much to do with electric currents, it is of the utmost importance that we get a clear conception of these three terms:

(*a*) **current** (rate of flow of electricity),
(*b*) **resistance** (opposition which regulates the flow),
(*c*) **voltage** (moving force which causes the flow).

The following table will help to fix the meaning of the units, ampere, ohm, and volt.

Units of	Water	Electricity
Quantity	Gallon	Coulomb
Current Quantity per second	**Gallon per second**	**Ampere** Coulomb per second
Resistance	(No unit)	**Ohm**
Motive force	**Feet of head**	**Volt**

279. Ohm's law. We have just learned that we cannot have a current flowing in a circuit unless there is an electromotive force to make it flow, and that the amount of the current is regulated by the resistance of the circuit. When water is forced through a pipe by a pump, the stream which flows is *directly* proportional to the pressure exerted by the pump and *inversely* proportional to the frictional resistance of the pipe. In the same way, when a current of electricity is forced along a wire, the current is *directly* proportional to the electromotive force, or voltage, of the cell or other generator and *inversely* proportional to the resistance of the circuit. This relation between current, electromotive force, and resistance is

Fig. 310. Georg Simon Ohm (1787–1854) German physicist and discoverer of the law in electricity bearing his name.

called **Ohm's law**, because Ohm (Fig. 310) was the first scientist who formally announced it (in 1827). The law may be stated thus: *The intensity of the electric current along a conductor equals the electromotive force divided by the resistance.*

$$\text{Current} = \frac{\text{electromotive force}}{\text{resistance}}.$$

In electrical units:

$$\text{Amperes} = \frac{\text{volts}}{\text{ohms}}.$$

In symbols: $I = \frac{E}{R}$

where I = Intensity of current in amperes,
E = Electromotive force in volts,
R = Resistance in ohms.

FOR EXAMPLE, suppose we want to find the intensity of the current sent through a resistance of 5 ohms by an electromotive force of 110 volts.

$$I = \frac{E}{R} = \frac{110}{5} = 22 \text{ amperes.}$$

If we want to find the electromotive force required to maintain a certain current in a circuit of known resistance, we have

$$E = IR.$$

FOR EXAMPLE, suppose we want to find the voltage required to send 10 amperes through an arc lamp if the resistance (hot) is 5.5 ohms.

$$E = IR = 10 \times 5.5 = 55 \text{ volts.}$$

If we need to find the resistance to be inserted in a circuit so that the current will have a given intensity when a known voltage is applied, we use our fundamental equation in this form:

$$R = \frac{E}{I}.$$

FOR EXAMPLE, suppose an electric heater can safely carry 10 amperes. If the heater is used on a 115-volt circuit, what must be the value of its hot resistance?

$$R = \frac{E}{I} = \frac{115}{10} = 11.5 \text{ ohms.}$$

Since Ohm's law is the foundation of all scientific knowledge of electric currents, the student will do well to commit it to memory and will save himself much work if he learns the law in its *three* forms.

It may be useful to point out here that the relation expressed in Ohm's law is a GENERAL PRINCIPLE which is found to hold true throughout the workings of nature; namely, that ***the result is proportional to the ratio of the applied force to the resistance.***

PROBLEMS

1. How much current flows through an arc lamp which has 15 ohms resistance when 75 volts are applied to it?

2. What current is produced by 12 volts acting through 0.25 ohms?

3. How much electromotive force is needed to send 2.5 amperes through (*a*) 2 ohms? (*b*) 50 ohms?

4. What is the hot resistance of a lamp filament which uses 0.4 amperes, at 115 volts?

5. An electric heater of 30 ohms resistance can safely carry 4 amperes. How high can the voltage run?

6. An electromagnet takes 5 amperes from a 115-volt line. How much would it draw from a 230-volt line?

7. A certain electric bell requires 0.25 amperes. The resistance of the coils in the bell is 12 ohms. What voltage is needed?

8. The resistance of a telephone receiver is 80 ohms, and the current required is 0.007 amperes. What voltage must be impressed across the receiver?

9. If the voltage on a trolley system is 550 volts, what current will flow through a car heater whose resistance is about 100 ohms?

10. An electric soldering iron takes 1.2 amperes when used on a 115-volt circuit. What is the resistance of the iron?

280. Measurement of current and voltage. We have already seen that by inserting a water meter in a pipe we can easily measure the quantity of water passing through in any period of time. Then we can readily compute the average rate of flow, or the quantity flowing past any point per second.

To measure the rate of flow of an electric current, we have simply to insert an ammeter (contracted from amperemeter).

Figure 311 shows an ammeter inserted in the circuit of an electric lamp to measure the current flowing through the lamp. It will be seen that all the current passing through the lamp must go through the ammeter. The ammeter itself has very little resistance; it is built as delicately as a watch, and so must be handled with great care. It will also be noted that the ammeter is connected so that the current enters the instrument at the plus (+) binding post and leaves at the minus (−) terminal.

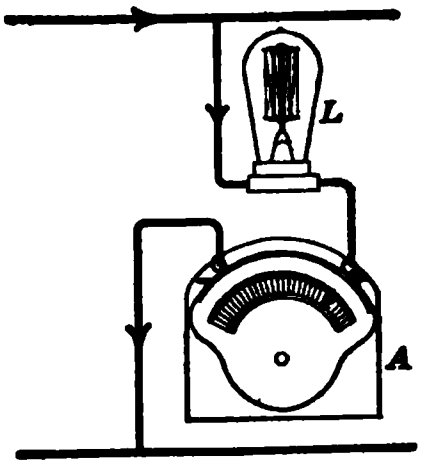

Fig. 311. The ammeter *A* measures the current flowing through the lamp *L*.

To measure the electromotive force, or voltage, which causes a current to flow through any electrical apparatus, we do not break the circuit or interrupt the current flowing through it. We simply tap the terminals of the voltmeter on to the terminals of the apparatus. It will be seen that the current which flows through the apparatus does not flow through the voltmeter.

Figure 312 shows how a voltmeter should be connected to measure the electromotive force which causes current to flow through a lamp. It will be seen at once that the voltmeter is connected across the lamp, so that the plus (+) binding post of the voltmeter is joined to the plus (+) side of the lamp. The voltmeter is an instrument of very high resistance and so draws only a very small current through itself.

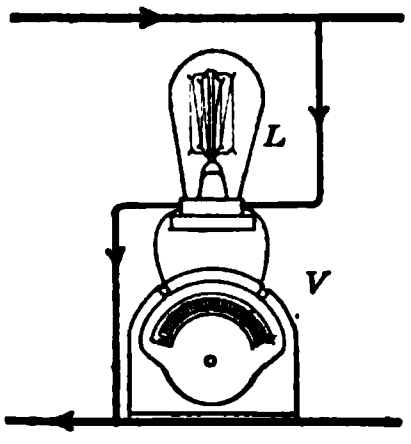

Fig. 312. The voltmeter *V* measures the voltage across the lamp *L*.

It is very important to learn the correct use of the ammeter and voltmeter. An ammeter is **inserted into the circuit**, while the voltmeter is **merely tapped across** the circuit. *If an ammeter were* by mistake *tapped across a line, it would instantly be burned out by the big surge of current.*

281. Measurement of resistance. Voltmeter and ammeter method. The simplest method of measuring resistance, wherever extreme accuracy is not required, makes use of the common instruments, voltmeter and ammeter. Suppose the unknown resistance to be measured is R. It is connected in series with the ammeter, and the voltmeter is placed across the unknown resistance, as shown in figure 313. Applying Ohm's law, we have the resistance equal to the voltage divided by the current; that is,

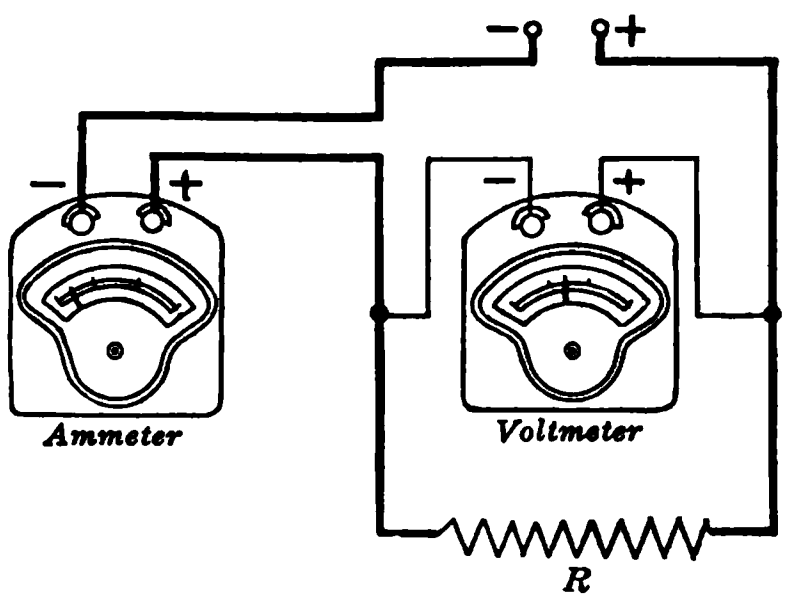

Fig. 313. The voltmeter-ammeter method of measuring the resistance R.

$$R = \frac{E}{I}.$$

NOTE. When the resistance to be measured is high, and the current in the circuit is small, the voltmeter is generally connected around *both* the resistance and the ammeter; because voltage across the ammeter is a smaller fraction of the whole voltage than the current through the voltmeter is of the whole current.

282. Computation of the resistance of a wire. The resistance of a wire depends upon four things: *its material, length, cross section*, and *temperature*. Experiments show that the resistance of any conductor varies directly as its length and inversely as its area of cross section.

Since wires are usually round, it is inconvenient to compute their area of cross section in square inches. Consequently electrical engineers call a wire which is one thousandth (0.001) of an inch in diameter **1 mil** in diameter, and its area of cross section **1 circular mil.** Inasmuch as the areas of circles vary as the squares of their diameters, *the area of a wire expressed in circular mils is equal to the square of its diameter expressed in mils.*

FOR EXAMPLE, a wire which is 15 mils in diameter is $(15)^2$, or 225 circular mils in cross section. A wire which is 1 inch in diameter is 1000 mils in diameter and 1 million circular mils in area. A square inch is $4/\pi$ million circular mils in area (Fig. 314).

The resistance of a wire is usually computed by comparing it with the resistance of a piece of wire of the same material which is 1 foot long and 1 circular mil in area of cross section. Such a piece of wire is called a **mil foot** of wire.

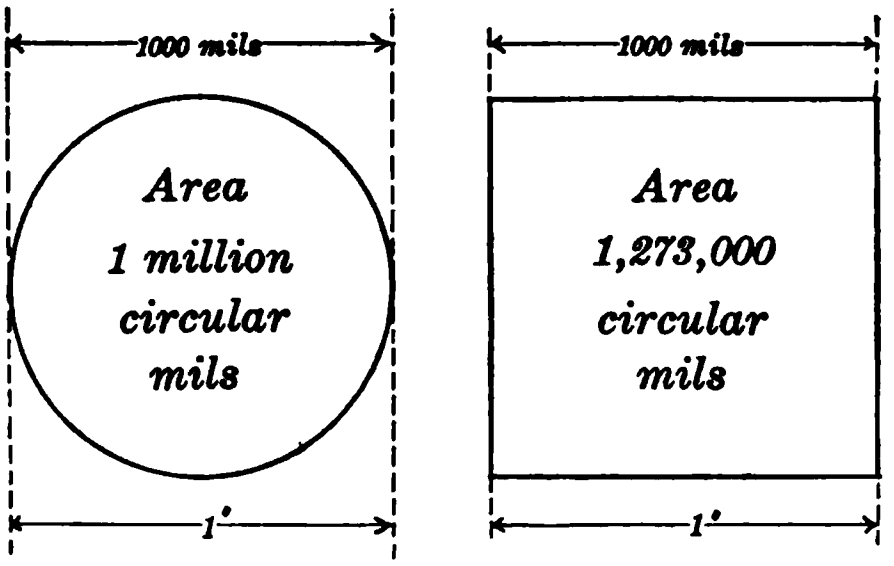

Fig. 314. A circle and a square in circular mils.

The resistance of a mil foot of wire is sometimes called the **resistivity** or **specific resistance** of the substance of which the wire is made.

For example, the specific resistance in ohms per mil foot of copper at 20° C. is about 10.4, of aluminum 18.7, and of iron 64.

We can readily compute the resistance of any wire *by multiplying the resistance of a mil foot of the wire* (given in ohms) *by the total length in feet, and dividing by its cross section in circular mils.*

This may be expressed, for convenience, as follows:

$$R = \frac{Kl}{d^2}$$

where R is the resistance in ohms, K the resistance of a mil foot (which is 10.4 ohms for copper at 20° C.), l the length in feet, and d^2 the circular mils in cross section.

FOR EXAMPLE, in computing the resistance of 500 feet of copper wire which is 40.3 mils in diameter, we have

$$R = \frac{Kl}{d^2} = \frac{10.4 \times 500}{(43.2)^2} = 3.2 \text{ ohms.}$$

Problems

1. Find the area of cross section in circular mils of a round wiro $\frac{1}{4}$ of an inch in diameter.

2. What is the diameter (mils) of a wire whose cross-sectional area is 22,500 circular mils?

3. What is the resistance of a mile of copper wire 0.25 inches in diameter?

4. How long must a copper wire 0.064 inches in diameter be to have a resistance of 10 ohms?

5. What is the diameter of a copper wire if a piece 1000 feet long has a resistance of one ohm?

6. What is the resistance of a mile of aluminum wire 0.204 inches in diameter?

7. A copper rod 1 inch in diameter and 10 feet long is drawn out into wire 0.1 inches in diameter. What is the resistance (*a*) of the rod; (*b*) of the wire?

8. Copper weighs 0.32 pounds per cubic inch. A coil containing 1000 feet of wire weighs 38.4 pounds. (*a*) What is the area of the wire in circular mils? (*b*) What is the resistance of the coil?

283. Use of a copper-wire table. Copper wire is ordinarily manufactured only in certain standard sizes. In this country these sizes are arranged according to the Brown and Sharpe (B. & S.) Gauge, sometimes called the American Wire Gauge (A.W.G.). The table on page 321 gives a list of the standard sizes, of which only the even numbers are in general use, except in the very small sizes. The second column shows the diameter of each gauge number in *mils* (0.001″). The third column gives the area of cross section in *circular mils*, which we have already learned is the square of the diameter in mils. The fourth column gives the resistance per thousand feet at 20° C. The use of this table greatly simplifies all wire computations. It will be seen that the wires grow smaller as the numbers increase and that every third gauge number **halves** the area of cross section and **doubles** the resistance.

Resistance of Soft or Annealed Copper Wire

B. & S. Gauge No.	Diameter in Mils, d	Area in Circular Mils, d^2	Ohms per 1000 Ft. at 20° C. or 68° F.	B. & S. Gauge No.	Diameter in Mils, d	Area in Circular Mils, d^2	Ohms per 1000 Ft. at 20° C. or 68° F.
1	289.30	83,694	0.1237	21	28.462	810.10	12.78
2	257.63	66,373	0.1560	22	25.347	642.40	16.12
3	229.42	52,634	0.1967	23	22.571	509.45	20.32
4	204.31	41,742	0.2480	24	20.100	404.01	25.63
5	181.94	33,102	0.3128	25	17.900	320.40	32.31
6	162.02	26,250	0.3944	26	15.940	254.10	40.75
7	144.28	20,816	0.4973	27	14.195	201.50	51.38
8	129.49	16,509	0.6271	28	12.641	159.79	64.79
9	114.43	13,094	0.7908	29	11.257	126.72	81.70
10	101.89	10,381	0.9972	30	10.025	100.50	103.0
11	90.742	8,234.0	1.257	31	8.928	79.70	129.9
12	80.808	6,529.9	1.586	32	7.950	63.21	163.8
13	71.961	5,178.4	1.999	33	7.080	50.13	206.6
14	64.084	4,106.8	2.521	34	6.305	39.75	260.5
15	57.068	3,256.7	3.179	35	5.615	31.52	328.4
16	50.820	2,582.9	4.009	36	5.000	25.00	414.2
17	45.257	2,048.2	5.055	37	4.453	19.82	522.2
18	40.303	1,624.3	6.374	38	3.965	15.72	658.6
19	35.890	1,288.1	8.038	39	3.531	12.47	830.4
20	31.961	1,021.5	10.14	40	3.145	9.89	1,047.

Problems

1. What is the resistance per mile of No. 10 copper wire?

2. What size of copper wire has about 2.5 ohms per mile?

3. A coil of No. 20 wire is found to have a resistance of 40 ohms. How many feet are there in the coil?

4. An electromagnet contains a coil of 800 turns of No. 24 copper wire. If the average length of a turn is 10 inches, what is the resistance of the coil?

5. What is the resistance of 1000 feet of cable made up of 91 wires, each No. 14 in size?

284. Effect of temperature on resistance. If we coil about 10 feet of No. 30 iron wire around a piece of asbestos board and send a current through it, we find by means of an ammeter in series with the coil (Fig. 315) that as we heat the wire in a Bunsen flame, the intensity of the current becomes greatly reduced.

Fig. 315. Heating the iron wire increases its resistance and decreases the current, as shown by the ammeter.

Experiments show that while the resistance of 1 mil foot of copper wire at 20° C. (68° F.) is 10.4 ohms, yet at 0° C. it is 9.6 ohms. The resistance of a one-ohm coil of copper, correct at 0° C., increases as the temperature rises, approximately 0.00426 ohms for each degree. By carefully measuring the resistance of a wire when cold and then when hot, we have an electrical method of measuring temperature.

Most pure metals have nearly the same rate of increase of resistance with rise of temperature. Thus, the resistance of a tungsten (Mazda) lamp when cold is 20 ohms, but the resistance of the same lamp when the filament is white hot rises to 400 ohms. Most alloys of metals not only have a much higher resistance than the pure metals of which they are made, but are much less affected by temperature changes. For example, "manganin" is an alloy of copper, nickel, iron, and manganese, which has a specific resistance of from 250 to 450 ohms per mil foot, according to the proportion of the metals used; but its resistance shows scarcely any change with temperature.

There are a few substances, such as carbon, glass, and porcelain, which *decrease* in resistance when heated. For example, the resistance of a carbon-filament lamp when it is hot is about half of the resistance of the same filament when it is cold.

285. Series circuits. When several pieces of electrical apparatus are connected in tandem, or one after the other,

they are said to be **in series.** The current passes around its circuit in a single path and *is the same in all parts of the circuit,* no matter what the resistance may be. The path may be made up of different materials which are of various dimensions, but *the resistance of the whole is the sum of the resistance of all the parts.*

FOR EXAMPLE, suppose we have three pieces of apparatus joined in series, *A* 50 ohms, *B* 30 ohms, and *C* 16 ohms (Fig. 316). Then

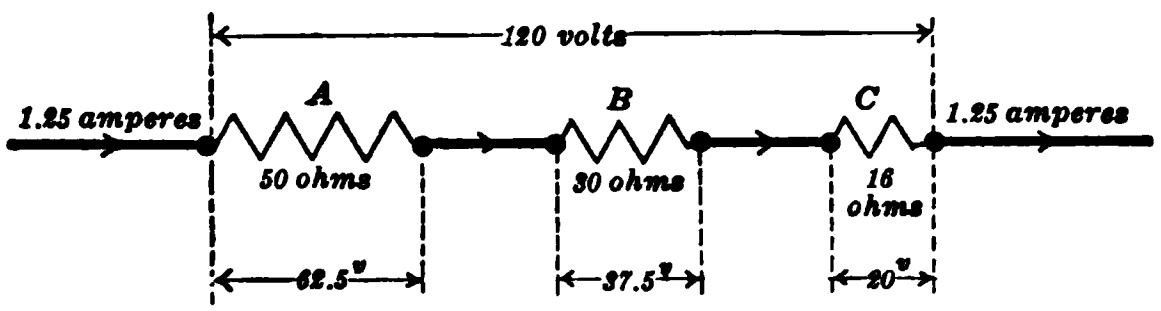

Fig. 316. Three resistances *A*, *B*, and *C*, joined in series.

the total resistance is the sum of these resistances, or 50 + 30 + 16 = 96 ohms. If these are connected to a 120-volt line, then the current according to Ohm's law is

$$I = \frac{E}{R} = \frac{120}{96} = 1.25 \text{ amperes.}$$

286. Application of Ohm's law to partial circuits. It is very important to remember that *Ohm's law applies not only to an entire circuit but also to any part of a circuit.* That is, the current in a certain part of a circuit equals the voltage across that same part divided by the resistance of the part.

FOR EXAMPLE, we wish to find the voltage across the 50-ohm resistance in the preceding problem. Since the current is 1.25 amperes, we have

$$E = IR = 1.25 \times 50 = 62.5 \text{ volts.}$$

The voltage across the 30-ohm resistance is

$$E = IR = 1.25 \times 30 = 37.5 \text{ volts.}$$

Finally, the voltage across the 16-ohm resistance is

$$E = IR = 1.25 \times 16 = 20 \text{ volts.}$$

The total voltage is the sum of these separate voltages, or

$$62.5 + 37.5 + 20 = 120 \text{ volts.}$$

The laws governing series circuits are as follows:

The current in every part of a series circuit is the same.

The resistance of several resistances in series is the sum of the separate resistances.

The voltage across several resistances in series is equal to the sum of the voltages across the separate resistances.

Moreover, since the voltage is equal to the resistance times the current ($E = IR$), and since the current (I) in every part of a series circuit is the same, it follows that the *voltage across any part of a series circuit is proportional to the resistance of that part.*

287. Parallel circuits. When two or more pieces of electrical apparatus are connected side by side so that the current is divided between them, they are said to be **in parallel** or **in multiple.**

Figure 317 shows two wires, whose resistances are 4 ohms and 6 ohms respectively, joined in parallel, and the voltage between their terminals (the points A and B) is 12 volts. Applying Ohm's law, we find the current flowing along the 4-ohm wire is $\frac{12}{4} = 3$ amperes, and that through the 6-ohm wire is $\frac{12}{6} = 2$ amperes. It will be seen that the larger current, 3 amperes, flows through the smaller resistance, 4 ohms. Also, the total current flowing through the circuit containing the two wires in parallel is 2 + 3, or 5 amperes. We may find the joint resistance of the two wires in parallel, or the resistance of the circuit between A and B, by applying Ohm's law. The voltage between A and B is 12 volts and the current is 5 amperes; therefore the resistance must be

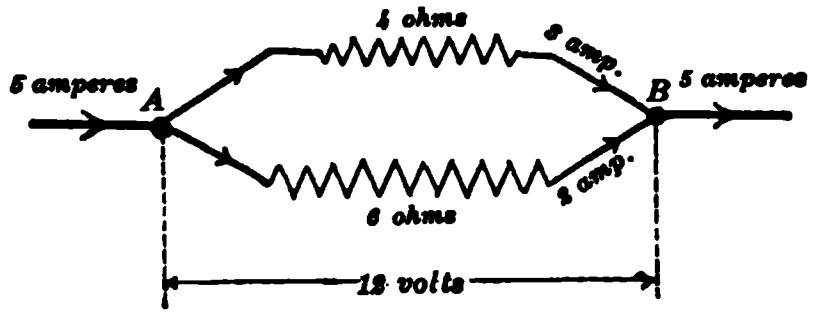

Fig. 317. Two wires joined in parallel.

$$R = \frac{E}{I} = \frac{12}{5} = 2.4 \text{ ohms.}$$

Thus we see that *the joint resistance of two wires in parallel is less than the resistance of either wire alone.* But this is explained by considering that the more paths we have in parallel

between A and B to carry the current, the less the resistance between those points. If we had three wires in parallel, the joint resistance would be still less.

This is quite like the case of two tanks at different levels and connected by three pipes. Evidently more water will flow through two pipes in a given time than through one alone, and still more will flow through three pipes. Hence, as pipes are added between the tanks, the resistance controlling the total flow of water is decreased.

To find the joint resistance of a parallel circuit, first find the current through each branch. Then add these currents to find the total current. Finally, divide the voltage across the parallel circuit by this total current. In case the voltage is not given, assume it to be one volt.

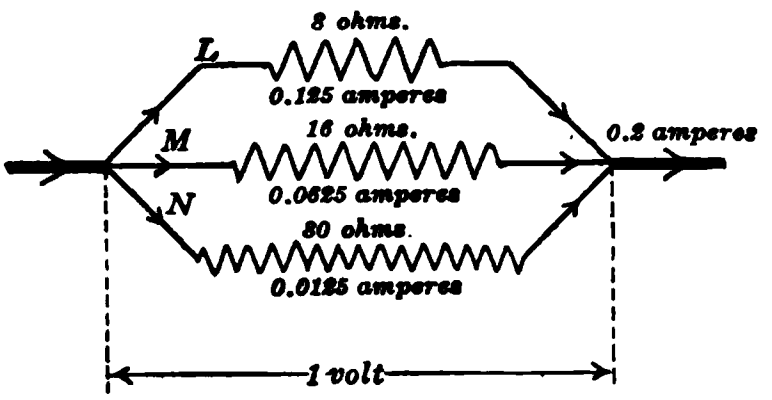

Fig. 318. Three resistances L, M, and N, joined in parallel.

FOR EXAMPLE, we have (Fig. 318) three resistances L, M, and N in parallel. $L = 8$ ohms, $M = 16$ ohms, and $N = 80$ ohms. Assume that the voltage across the combination is 1 volt.

Then the current in L is $\frac{1}{8}$, or 0.125 amperes, in M is $\frac{1}{16}$, or 0.0625 amperes, and in N is $\frac{1}{80}$, or 0.0125 amperes. The total current is $0.125 + 0.0625 + 0.0125 = 0.2$ amperes, and the joint resistance is $\frac{1}{0.2}$, or 5 ohms.

A little consideration of what precedes will show that when two wires of equal resistance are connected in parallel, their joint resistance is just half as great as the resistance of either wire. If three wires of equal resistance are connected in parallel, their joint resistance is just one third as great as the resistance of one of the conductors, and so on. If wires of equal resistance were connected in series instead of in parallel, the resistances would be two, three, and so on, times as great as that of a single wire.

The laws governing parallel circuits are as follows:

The voltage across several resistances in parallel is the same for all.

The total current through the combination is the sum of the currents through the parts.

The joint resistance of a parallel combination is equal to the voltage divided by the total current.

PROBLEMS

1. If a lamp having 45 ohms resistance is joined in series with a coil of 10 ohms across a 110-volt circuit, what is the resistance of the two pieces joined in series? What is the current?

2. Three resistances, 200, 200, and 40 ohms, are connected in series across a 220-volt line. What is the resistance of this part of the circuit? What current flows in this circuit?

3. If five lamps of 15 ohms each are inserted in series in a line whose resistance is 4 ohms, what is the total resistance? What voltage is needed to send 7 amperes through the lamps?

4. A lamp of 55 ohms, another lamp of 30 ohms, and a coil of 15 ohms are connected in series. The voltage across the 30-ohm lamp is 120 volts.

Find:

(*a*) The current in the lamps and the coil.
(*b*) The voltage across the 55-ohm lamp.
(*c*) The total voltage.

5. Three resistances, one 30 ohms, another 40 ohms, and the third unknown, are connected in series with an ammeter which reads 2.5 amperes. Total voltage on the line is 225 volts.

Find:

(*a*) The unknown resistance.
(*b*) The voltage across 30 ohms.
(*c*) The voltage across 40 ohms.

6. What is the joint resistance of three parallel branches, each of which has a resistance of 120 ohms?

7. What is the joint resistance of two parallel branches which have resistances of 40 and 60 ohms respectively?

8. If the resistance of a wire is 4 ohms, what must be the resistance of another which, when put in parallel with it, makes the joint resistance 3 ohms?

9. What is the joint resistance of three wires in parallel which have resistances of 1, 0.5, and 0.2 ohms respectively?

10. If ten similar lamps, connected in parallel, have a joint resistance of 20 ohms, what is the resistance of each lamp?

11. An electromotive force of 150 volts is impressed on a parallel circuit which consists of four branches of 2, 4, 5, and 10 ohms respectively. (*a*) What current will flow in each branch? (*b*) What will be the total current through the combination?

12. What voltage is needed to send 9 amperes through a parallel combination consisting of a 4-ohm and a 12-ohm branch?

13. A circuit has three branches of 12, 6, and 4 ohms respectively. If the current in the 6-ohm branch is 4 amperes, what current will flow in each of the others?

288. Cells in series. Not only may the separate *external* resistances be arranged in series, but the *cells*, or generators, themselves may be so arranged. Figure 319 shows three dry cells connected in series: that is, the carbon (or + pole) of cell No. 1 is connected to the zinc (or − pole) of cell No. 2; the carbon of No. 2 is connected to the zinc of cell No. 3; and the current for the external circuit is led off from the carbon of cell No. 3. After passing through the external circuit, the current returns to the zinc of cell No. 1. Thus we see that the current flows through each cell in succession.

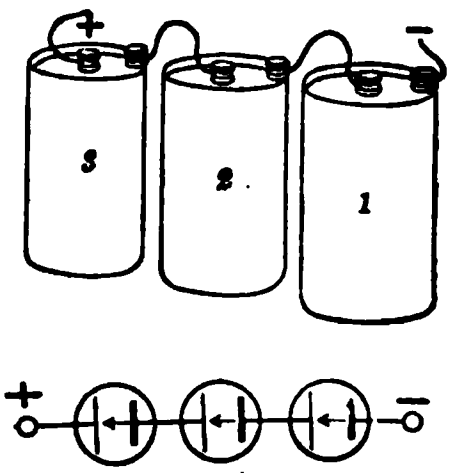

Fig. 319. Three cells connected in series.

If we test one dry cell with a voltmeter, we find that it gives an electromotive force of about 1.5 volts, two cells in series give 3.0 volts, and three cells in series give 4.5 volts; so *the e.m.f. of a combination of cells in series is the sum of the e.m.f.'s of the cells.*

It may help us to understand why the e.m.f. of cells in series is the sum of the several e.m.f.'s if we think of the first cell as pumping the electricity up to a certain electrical potential

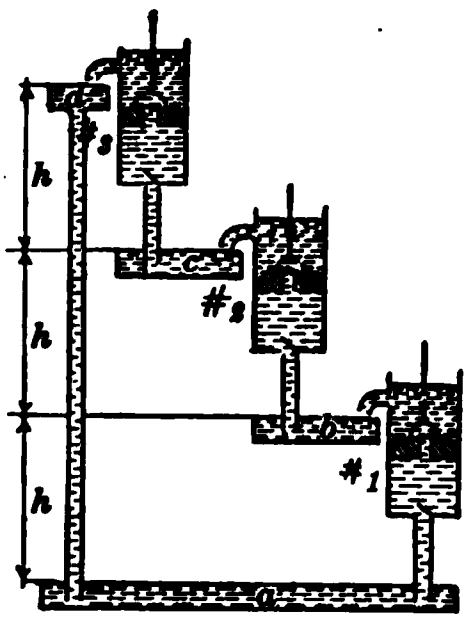

Fig. 320. Water analogue of three cells in series.

(or level), and the next cell as pumping it to a still higher potential and so on. Figure 320 shows the water analogy of 3 cells in series.

Of course, the internal resistance of a combination of cells in series, like the resistance of any series circuit, is the sum of the internal resistances of the single cells.

289. Cells in parallel. Any combination of two or more cells is called a **battery.** Sometimes it is advantageous to arrange cells, or generators, in parallel. Figure 321 shows a battery of three dry cells arranged in parallel; that is, all the positive terminals (carbons) are connected together and so are all the negative terminals (zincs). If we test the e.m.f. of this parallel combination, we find that *the voltage of a parallel battery is the same as the voltage of one cell.*

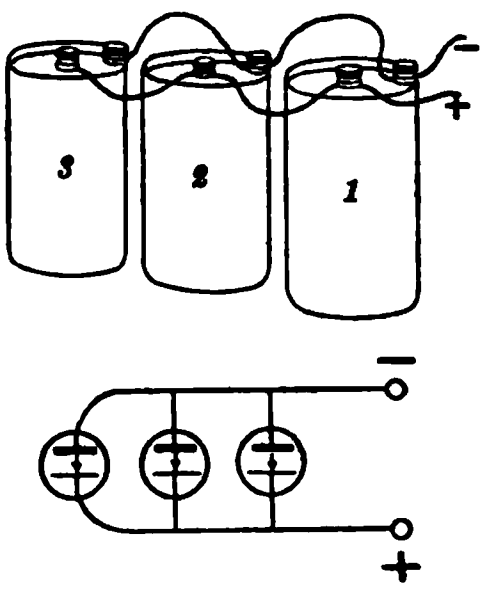

Fig. 321. Three cells connected in parallel.

It will help us to understand why the e.m.f. of cells in parallel is no greater than that of a single cell if we think of each cell as pumping the electricity up to a certain electrical potential (or level) and all the cells as working side by side. Figure 322 shows the water analogy of cells in parallel.

The *internal resistance* of a parallel battery, like that of any other parallel combination, *is the resistance of one cell divided by the number of cells.*

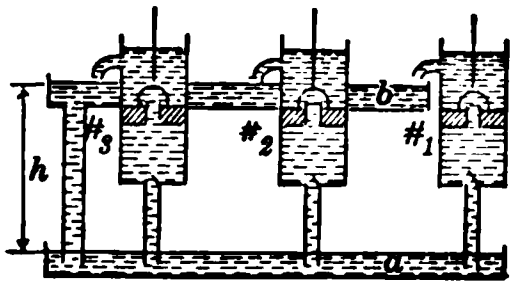

Fig. 322. Water analogue of three cells in parallel.

FOR EXAMPLE, suppose that 3 cells are in parallel, that the voltage of each cell is 1.5 volts, and that the resistance of each cell is 0.12 ohms. What will be the current through an external resistance of 0.26 ohms?

The internal resistance of the battery is $\frac{0.12}{3}$, or 0.04 ohms. The total resistance is the sum of the internal and external resistances, $0.26 + 0.04 = 0.3$ ohms. By Ohm's law the current through the external resistance is $\frac{1.5}{0.3}$, or 5 amperes.

Then the current in each cell will be $\frac{1}{3}$ of 5 amperes, or 1.67 amperes.

290. Best arrangement of cells. Given 6 dry cells, it would be possible to arrange these cells in two other ways besides all in series or all in parallel. For example, we might arrange them in two rows of three cells each, join the cells in each row in series, and then connect the rows in parallel, as shown in figure 323. It would also be possible to arrange the six cells in 3 rows, each consisting of 2 cells in series, the rows being connected in parallel (Fig. 324).

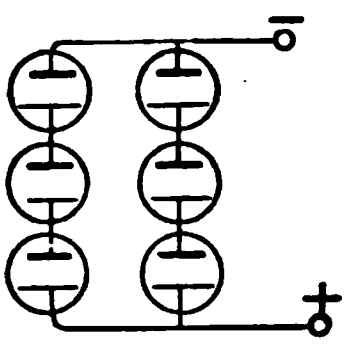

Fig. 323. Six cells connected 3 in series and 2 in parallel.

To find the current which any combination of cells will force through a given resistance: *first*, find the total voltage, that is, the volts per cell times the number of cells in series; *second*, find the internal resistance, which is the resistance of one cell times the number of cells in series divided by the number of parallel rows; *third*, find the total resistance, that is, the sum of external and internal resistances; *finally*, apply Ohm's law, that is, divide the total voltage by the total resistance.

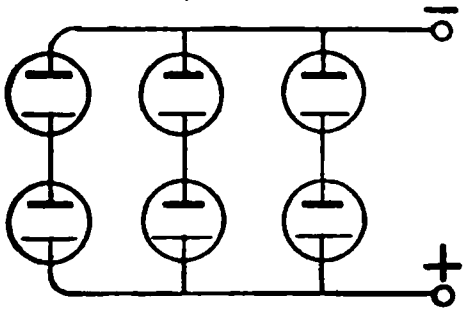

Fig. 324. Six cells connected 2 in series and 3 in parallel.

It can be proved that *the maximum current is obtained by arranging the cells so that the internal resistance of the whole combination of cells is as nearly as possible equal to the external resistance.*

Therefore, to get the greatest current through a given resistance, if the **external resistance is large**, arrange the **cells in series**; but if the **external resistance is very small**, arrange the **cells in parallel.**

In practical work the external resistance is usually large compared with the internal resistance; hence cells are generally arranged in series.

Problems

1. Find the current which each of the four arrangements of the 6 cells described in the preceding section would send through an external resistance of 10 ohms. Assume that the voltage of each cell is 1.5 volts and that the internal resistance of each cell is 0.12 ohms.

2. Find the current which each of these four arrangements of 6 cells would send through an external resistance of 0.1 ohms.

291. Internal construction of a dry cell. During the last few years, what is called a "dry" cell has come to be practically the only type of cell used for open-circuit or intermittent work, such as ringing bells, and operating telephones, signal devices, flash lights, and the ignition circuits of gas engines. In this cell (Fig. 325) the negative plate is a zinc can, which serves as the containing vessel, and the positive plate is a carbon rod, which may be either cylindrical or fluted. The zinc can is lined with an absorbent layer of pulp board or blotting paper which is saturated with a water solution of sal ammoniac and zinc chloride. The space between the lining and the carbon is filled with a paste made of granulated carbon and manganese dioxide soaked in a water solution of sal ammoniac. This mixture fills the cell to within about an inch of the top. The top of the cell is generally sealed up with a pitch composition. The outside of the zinc can is frequently lacquered and the cell is always set in a close-fitting cardboard container. The sal ammoniac in this cell takes the place of the sulfuric acid in the simple cell described above.

Fig. 325. Cross section of a dry cell.

About eighty per cent of the dry cells manufactured in this country (about fifty million each year) are made with a zinc can 6 inches high and 2.5 inches in diameter. Such a cell when new should give, when tested with an ammeter (Fig. 326), at least 15 amperes and not more than 25 amperes. Much smaller dry cells are made for flash lights. Tests

with a voltmeter will show that *the size of a cell makes no difference in its voltage.*

292. How long will a dry cell last? The "life" of a dry cell is not a fixed quantity but depends on the circuit in which it is used. Oftentimes dry cells which are merely standing on a shelf for a year without being used at all will dry up and become practically useless. Sometimes a battery of 5 dry cells, such as would be used for the ignition of a gas engine which is in pretty constant use, will last for two months. The working life of a dry cell depends on the length of time that its circuit is left closed, but may be extended by arranging the circuit so that the current drawn from any one cell will be small.

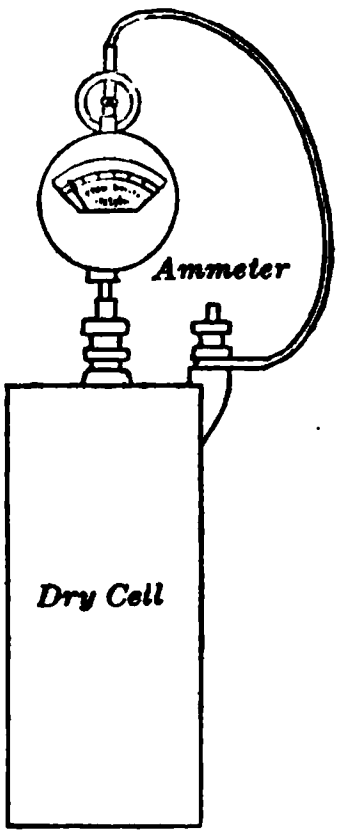

Fig. 326. Testing a dry cell.

In an old dry cell holes will often be found in the zinc can. This means that the metal has been consumed by the chemical change which furnished the energy to drive the electricity through the cell and the external circuit. Thus we see that the *zinc acts as the fuel*, very much as coal is used to furnish the energy to drive water through pipes. The rate at which this electrical energy is delivered by the cell determines the rate at which the zinc is used up; just as the rate at which steam energy is delivered to a boiler determines the rate of coal consumption. A large cell will naturally last longer than a small cell because it contains more zinc. It is on account of the expense of using zinc as a fuel that we employ cells only as a source of very small electric currents, and use electric generators (Chapter XVII) for supplying power for domestic and commercial purposes.

293. Polarization in dry cells. It was long ago discovered that when a simple electric cell is used by connecting the terminals with a wire, *the current does not remain constant* but rapidly becomes weaker. This effect, called **polarization**, was found to be caused by the formation of a gas, usually hydrogen, on the positive plate. This layer of gas increases the internal resistance of the cell and also sets up an opposing electromotive

force. In the dry cell the manganese dioxide is put in to act as a depolarizer. Nevertheless, because of this polarization, a *dry cell cannot be left on a closed circuit for any length of time.*

294. Terminal voltage of a cell. If we connect a voltmeter to a dry cell, we find that its e.m.f. is about 1.5 volts. If we connect a coil of high resistance (1000 ohms) across the terminals, the terminal voltage, as indicated by the voltmeter, is very nearly the same as before. But if we connect a short, thick wire across the terminals (short-circuit the cell) so as to draw a large current, we see by the voltmeter that the terminal voltage is much less than before.

From this experiment it is evident that the terminal voltage of a cell which is delivering current is always less than its electromotive force, or its open-circuit voltage. We may understand this fact if we remember that voltage is used to send the current through the internal resistance of the cell; just as voltage is used to send a current through any other kind of resistance.

FOR EXAMPLE, if the e.m.f. of a dry cell is 1.5 volts and its internal resistance is 0.07 ohms, what is the terminal voltage when it is delivering 5 amperes?

$$\begin{aligned}\text{Volts used in overcoming int. rest.} &= \text{current} \times \text{internal resistance}\\ &= 5 \times 0.07\\ &= 0.35 \text{ volts.}\end{aligned}$$

$$\begin{aligned}\text{Terminal voltage} &= \text{e.m.f.} - \text{volts used on internal resistance}\\ &= 1.5 - 0.35\\ &= 1.15 \text{ volts.}\end{aligned}$$

If the current is 10 amperes, the terminal voltage is $1.5 - 10 \times 0.07$, or 0.8 volts.

Since some of the electromotive force of a cell must always be used in sending current through its internal resistance, it is essential that this internal resistance be as low as possible, especially when the cell is to furnish a large current.

295. Voltage drop in a line. We have just seen that the terminal voltage of a battery is less than its electromotive force because of the voltage required to send the current

through the internal resistance of the battery. Similarly when an electric current is used at a considerable distance from the generator, the voltage at the receiving end of the line is always less than the generator voltage. This **voltage drop in the line** is equal to the current times the resistance of

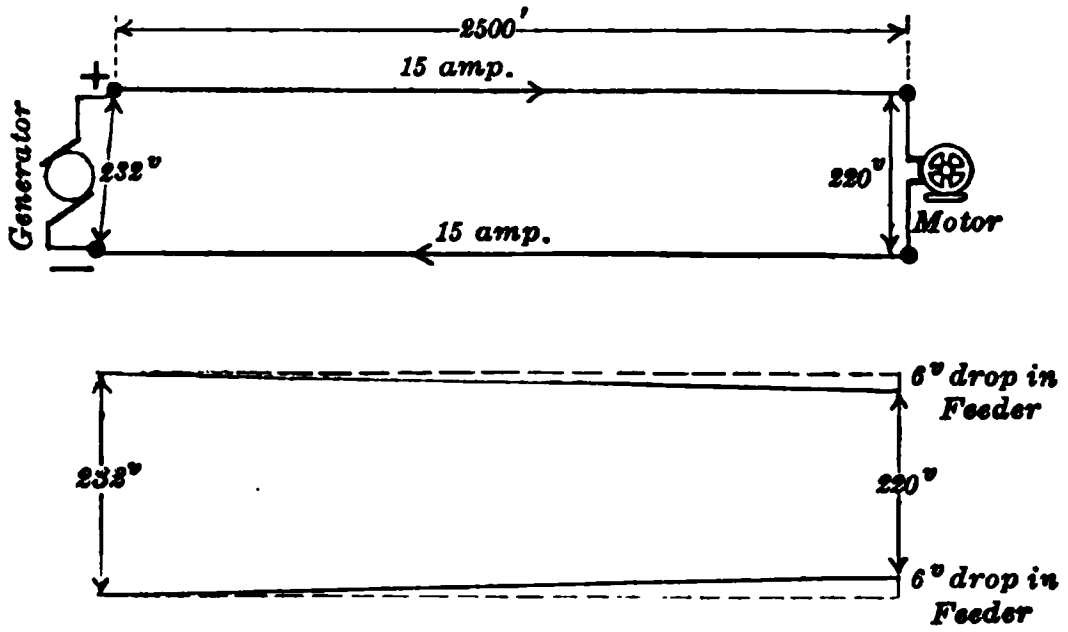

Fig. 327. Voltage drop in a line is the voltage required to send the current through the line.

the line (IR). The voltage drop in ordinary practice for house wiring should not exceed 2 per cent.

If we know the length and the size of a line wire and the current it is to carry, we can compute the voltage drop.

For example, what is the voltage drop in 1500 feet of No. 4 copper wire carrying 40 amperes?

According to the wire table (page 321), 1000 feet of No. 4 wire has a resistance of 0.248 ohms, and the resistance of 1500 feet would be 1.5×0.248, or 0.372 ohms. The voltage drop $E = IR = 40 \times 0.372 = 14.9$ volts.

Again, suppose the voltage drop allowable in sending 15 amperes through 5000 feet of wire is 12 volts (Fig. 327). What size wire is required?

Compute the resistance by Ohm's law:

$$R = \frac{E}{I} = \frac{12}{15} = 0.8 \text{ ohms.}$$

Then the resistance of 1000 feet of this wire is $\frac{0.8}{5}$, or 0.16 ohms. According to the table, this resistance requires a wire between No. 2 and No. 3, and therefore we should use the larger size, that is, No. 2.

Problems

1. A dry cell when tested with a voltmeter showed 1.5 volts, and when tested with an ammeter whose resistance was negligible, gave 7.5 amperes. Find the internal resistance of the cell.

2. If the voltage drop in a trolley line carrying 150 amperes is 12.5 volts, what is the resistance of the line?

3. What is the " line drop," that is, voltage drop, in a 4-mile copper wire carrying 100 amperes, if the wire is 0.325 inches in diameter?

4. If a group of lamps which takes 12 amperes is 500 feet from the generator, and if the line drop must not exceed 2.6 volts, what size of copper wire must be used?

Practical Exercises

1. Making and using a sal-ammoniac cell. For full directions see *Good's* Laboratory Projects in Physics (Macmillan).

2. Setting up a miniature light and power system. Follow the directions in *Good's* Laboratory Projects.

SUMMARY OF PRINCIPLES IN CHAPTER XV

Electric current flows *downhill*, from + to −, in *outside* circuit.

Current is pumped *uphill*, from − to +, *inside* of cell, or generator.

Unit of current is *ampere*. Corresponds to gallons per second.

Unit of resistance is *ohm*. Corresponds to friction in pipe.

Unit of e.m.f. is *volt*. Corresponds to head of water.

Ohm's law:

$$\text{Current} = \frac{\text{electromotive force}}{\text{resistance}}.$$

Applies to whole circuit or to any part of circuit.

If applied to whole circuit, one must take account of *internal resistance* of cell, as well as of *external resistance*.

Ammeter — low resistance — put in series — carries whole current.

Voltmeter — high resistance — put across circuit — diverts small current.

Resistance of wire =

$$\frac{\text{specific resistance (mil foot)} \times \text{length (feet)}}{\text{square of diameter (mils)}^2}.$$

For *resistances* in series —

Current everywhere the *same*.

Resistance of combination is *sum* of resistances of parts.

Voltage across combination is *sum* of voltages across parts.

For *resistances* in parallel —

Voltage across conductors is the *same* for all.

Total current through combination is *sum* of currents through parts.

Joint resistance is equal to voltage divided by total current.

For *cells* in series —

E.m.f. is *sum* of e.m.f.'s of the cells.

Resistance is *sum* of resistances of the cells.

Current is the *same* in each cell as in external circuit.

For *cells* in parallel —

E.m.f. is *same* as e.m.f. of one cell.

Resistance of n cells in parallel is $\frac{1}{n}th$ the resistance of any one alone.

Current in each cell is $\frac{1}{n}th$ the current in external circuit.

Electrical energy of a cell is supplied by chemical action of a solution on zinc. *Zinc is fuel of cell.*

E.m.f. of cell = total pump action of cell.

Terminal voltage less than e.m.f. by amount needed to keep current moving through internal resistance of cell.

Voltage drop in line is equal to current times resistance of line (IR).

QUESTIONS

1. Why is the study of electricity in motion so much more important than the study of electricity at rest?

2. Is it always true that a current of water is everywhere the same in a water main?

3. A copper wire and an iron wire of the same cross section are found to have the same resistance. Which is the longer?

4. What number (B. & S.) of copper wire has a resistance of practically 1 ohm per 1000 feet? What size copper wire has a resistance of practically 2 ohms per 1000 feet? How many numbers do you have to go up on the wire gauge to double the resistance of the wire?

5. Is it true that in a divided circuit an electric current "always takes the line of least resistance"? Explain.

6. How may the joint resistance of two parallel wires be found if the individual resistances are known?

7. Why is the joint resistance of wires in parallel never equal to the average of the separate resistances?

8. How may the joint resistance of several known equal resistances arranged in parallel be computed?

9. What other types of primary cells are sometimes used besides the dry cell? What advantages has the dry cell over other types?

10. Explain why a dry cell which is really dry is useless.

11. What would happen to a dry cell if you tried to recharge it from a generator?

12. How does the voltage drop in a given line vary with the current?

CHAPTER XVI

EFFECTS OF AN ELECTRIC CURRENT

Magnetic effect — Oersted's discovery — magnetic field about a current — a solenoid — electromagnet — applications in lifting magnets, bells, telegraph, d'Arsonval galvanometer, ammeter, and voltmeter.

Heating effect — fuses and circuit breakers.

Calculation of electric power — watts and kilowatts — electrical energy — kilowatt hours and joules.

Lighting — vacuum and gas-filled tungsten lamps — open, inclosed, flaming, metallic, and mercury arc lamps.

Chemical effects — electrolysis — electroplating — electrotyping — refining of metals — silver coulombmeter.

Storage batteries — lead and Edison.

Magnetic Effect of Electric Current

296. Oersted's discovery. In 1819 a Danish physicist, Oersted, made a discovery which aroused the greatest interest because it was the first evidence of a connection between magnetism and electricity. He found that if a wire connecting the poles of a voltaic cell was held *over* a compass needle, the north pole of the needle was deflected toward the west when the current flowed from south to north, as shown in figure 328; while a wire placed *under* the compass needle caused the north end of the needle to be deflected toward the east.

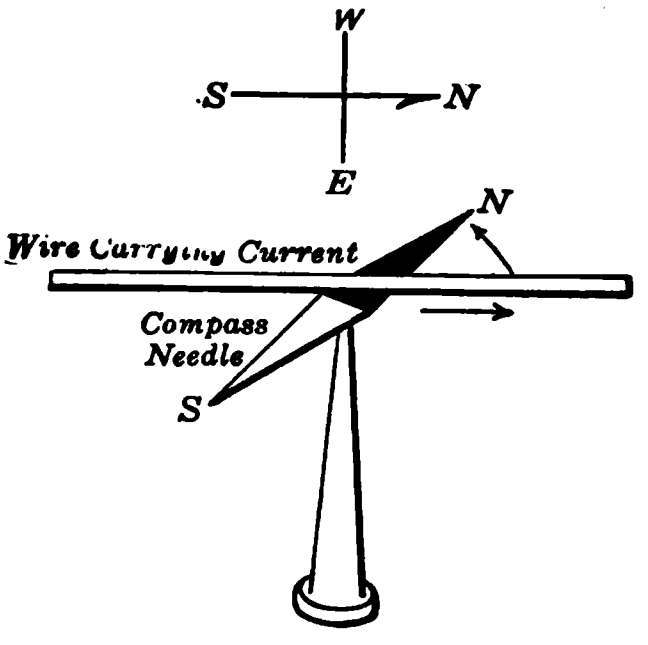

Fig. 328. Current in wire above compass needle deflects compass needle.

297. Magnetic field around a current. Inasmuch as the compass needle indicates the direction of magnetic lines of force, it is evident from Oersted's experiment that a current must set up a magnetic field at right angles to the conductor.

To make this clear, we send a strong current down a vertical wire which passes through a horizontal piece of cardboard. To indicate the magnetic lines of force, we sprinkle iron filings on the cardboard and tap it gently while the current is on. The filings arrange themselves in concentric rings about the wire. By placing a small compass at various positions on the board, we see that the direction of these lines of force is as shown in figure 329.

Fig. 329. Magnetic lines of force surround an electric current.

A convenient rule for remembering the direction of the magnetic flux around a straight wire carrying a current is the so-called **thumb rule.**

If one grasps the wire with the right hand (Fig. 330) *so that the thumb points in the direction of the current, the fingers will point in the direction of the magnetic field.*

If we know the direction of the magnetic field near a conductor, we can, by applying this rule, find the direction of the current.

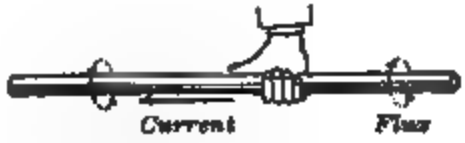

Fig. 330. Thumb rule for magnetic field around a wire.

298. Magnetic field around a coil. If a wire carrying a current is bent into a loop, all the lines of force enter the loop at

one face and come out at the other face. If several loops are put together to form a coil, practically all the lines will thread the whole coil and return to the other end outside the coil.

(1) We may thread a loose coil of copper wire through a board or sheet of celluloid in such a way that when iron filings are evenly scattered over the smooth surface of the board, while a strong current is sent through the wire, they will indicate the lines of magnetic force (Fig. 331). By tapping the board gently and using a small compass, we can see the general direction of the lines of magnetic flux. It will be noticed that there are a few circular lines around each wire, and that these lines go out between the loops. They are called the "leakage flux" of the coil.

Fig. 331. Magnetic flux around an open coil.

(2) If we send a current through a close-wound coil of insulated copper wire, and bring it near a compass needle, we find that it behaves like a bar magnet. If the current is reversed, the poles of the coil are reversed.

(3) If we put a soft-iron core inside the coil when the current is on, the iron exerts a very strong pull on bits of iron; but when the current is off, the iron loses this magnetism almost at once.

(4) If we use a large horseshoe electromagnet (Fig. 332), or a model of a magnetic hoist, and considerable current, we may show that a tremendous force can be exerted by an electromagnet.

An iron core in a coil of wire is so much more permeable than air that the same current in the same coil produces several thousand times as many lines of force in the iron core as it would in air alone.

Fig. 332. Electromagnet for demonstration purposes.

299. Electromagnet. An iron core, surrounded by a coil of wire, is called an

electromagnet. It owes its great utility not so much to the fact of its great strength, as to the fact that, if it is made of soft iron, *its magnetism can be controlled at will.* Such an electromagnet is a magnet only when current flows through its coil. When the current is stopped, the iron core returns almost to its natural state. This loss of magnetism is, however, not absolutely complete; a very little **residual magnetism** remains for a longer or shorter time.

Fig. 333. Rule for polarity of coil carrying current.

An electromagnet is a part of nearly every electrical machine, including the electric bell, telegraph, telephone, generator, and motor.

To determine its **polarity**, we shall find it convenient to express the thumb rule as used for a straight wire, in another way, as follows:

THUMB RULE FOR A COIL. *Grasp the coil with the right hand so that the fingers point in the direction of the current in the coil, and the thumb will point to the north pole of the coil* (Fig. 333).

The **strength** of an electromagnet depends on the product of the strength of the current (amperes), by the number of loops of wire (turns), that is, on the *ampere turns* of the coil.

Fig. 334. Joseph Henry (1799–1878). First American to study the electromagnet and the laws of electromagnetic induction.

It is the practice, in order to make use of both poles of an electromagnet, to bend the iron core and the coil into the shape of a horseshoe.

Applications of the Electromagnet

300. Lifting magnets. Practical electromagnets were made in 1831 by Joseph Henry (Fig. 334), a famous American schoolmaster and scientist, then teaching in the academy at Albany, N.Y., and by Faraday in England. Henry's magnet was capable of supporting fifty times its own weight, which was considered very remarkable at the time.

Magnetic hoists (Fig. 335) are now built so powerful that when the face of the iron core is brought in contact with iron or steel castings and the current is turned on, the magnets will lift from 100 to 200 pounds of iron per square inch of pole face, and yet release the load of iron the moment the current is cut off.

Fig. 335. Lifting magnet handling a ton of pig iron.

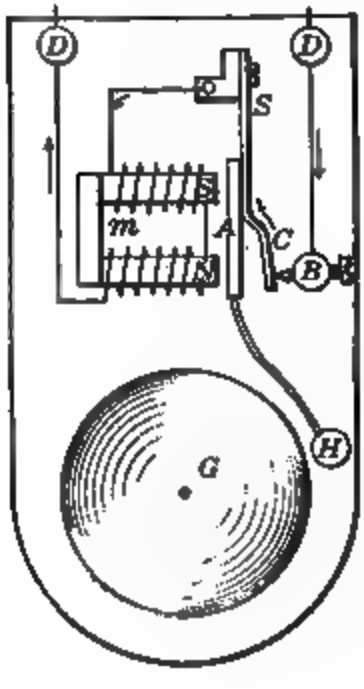

Fig. 336. Diagram of electric bell.

301. Electric bell. An electric-bell circuit usually includes a battery of two or more cells, a push button, and connecting wires, besides the bell itself (Fig. 336). When the circuit is closed by pushing the button, the current flows through the electric magnet *m* and attracts the armature *A*. As the armature swings to the left, it pulls the spring *C* away from the screw contact *B* and breaks the circuit. This stops the current, and the electromagnet releases the armature. It then springs back again and closes the circuit at the screw, and the whole process is repeated. The swinging of the armature, which carries a hammer, causes a series of rapid strokes against

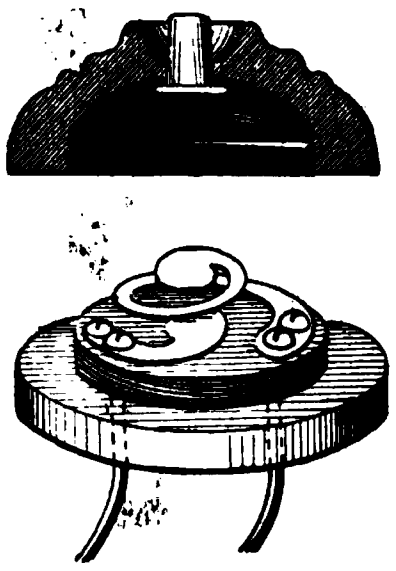

Fig. 337. Ordinary push button.

the bell. The construction of the ordinary push button is shown in figure 337.

302. Telegraph. The word "telegraph" means an instrument which "writes at a distance," for the early forms invented by Samuel F. B. Morse, in 1844, were designed to make dots and dashes on a moving strip of paper. Nowadays the receiving instrument, called the sounder, makes a series of clicks separated by short or long intervals of time to represent the dots and dashes, and the message is taken by ear rather than by eye.

The **telegraph** consists essentially of a battery, a key, and a sounder, as shown in figure 338. Storage cells are used in practical work, but for experimental purposes any kind of battery will serve.

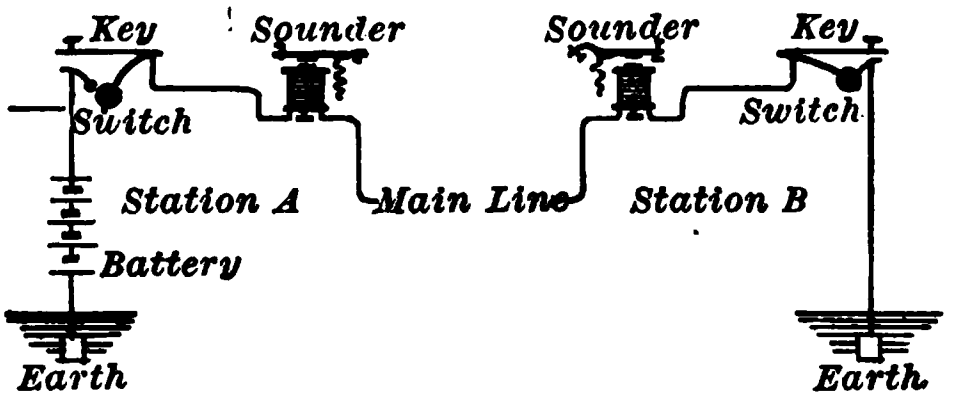

Fig. 338. Simple telegraph circuit.

The **key** (Fig. 339) is a device, something like a push button, for making and breaking the circuit. The **sounder** (Fig. 340) consists of an electromagnet with a soft-iron armature which is fastened to a metal bar. This bar is pivoted so as to move up and down. When a current flows through the electromagnet, the armature is pulled down; when the circuit is broken, a spring pushes the bar up again. Two set screws above and below the bar limit its motion and make the clicks. As the clicks made by the bar hitting these two set screws are different the ear recognizes the time between these two clicks as a dot or a dash according as the key is depressed a short or a long time.

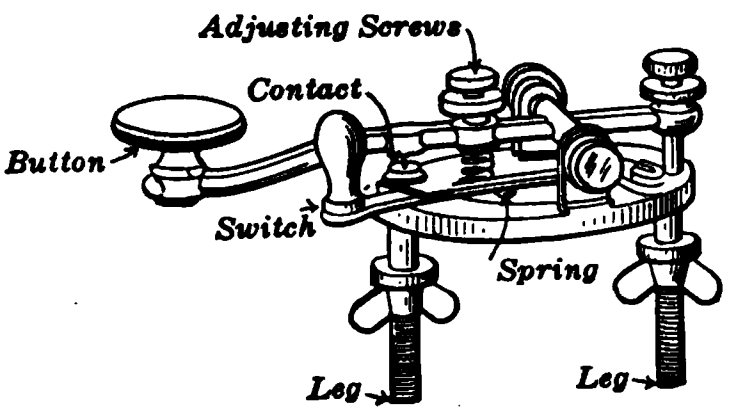

Fig. 339. Telegraph key.

When the telegraph came into commercial use, it was found that the resistance of the connecting wires, called the line, was so great that the current was too feeble to operate the sounder, even when many cells were connected in series. A relay (Fig. 341) is therefore employed to open and close the circuit of a local battery which operates the sounder. This relay contains an electromagnet whose coil has many turns of very small copper wire. In front of this magnet is a light iron lever which is held away from the electromagnet by a very delicate spring. The connections are shown in figure 342. When the key in the main circuit is closed, the weak current excites the relay magnet enough to pull the armature against a set screw, thus closing the local circuit which sends a strong current through the sounder.

Fig. 340. Telegraph sounder.

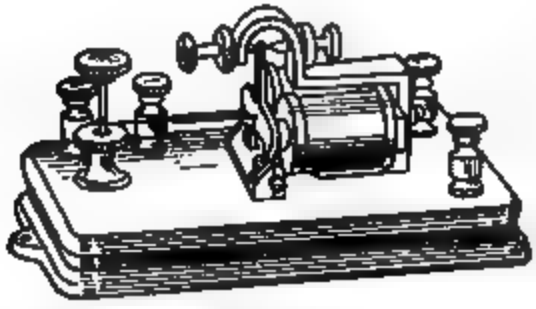

Fig. 341. Telegraph relay.

In ordinary telegraphy it is customary to use a single wire of galvanized iron or hard-drawn copper, and to use the earth as a return circuit. At each station along the line there is a local circuit consisting of battery and sounder, which is closed by a relay. The relay is operated by the main circuit containing a key and the main-line battery or generator. Each key is provided with a switch, so that the main circuit is kept closed everywhere except at the station where the operator is sending a message.

Submarine telegraphy began as early as 1837, but it was not till 1866 that a really successful Atlantic cable was laid. Its copper core and the steel sheath act like the coatings of an immense Leyden jar. The effect of this is to make the sending of messages very slow. The impulses received at the other end are also very weak. It was only when an exceedingly delicate receiving instrument had been devised by Lord Kelvin, that the first Atlantic cable could be used at all.

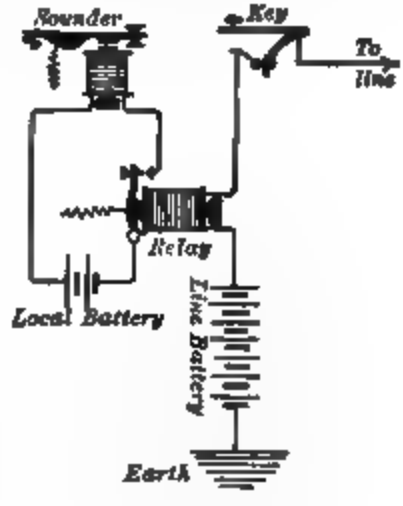

Fig. 342 Diagram of a telegraph relay circuit.

303. The d'Arsonval galvanometer. An instrument which measures or detects small electric currents is called a galvanometer. Modern galvanometers are built with a **moving coil** and **fixed magnet**; they are called the **d'Arsonval** type.

Figure 343 shows one form of galvanometer. The horseshoe magnet is large and is firmly fastened to the base; while the coil is suspended by a very fine wire or metallic ribbon, which also serves to lead the current out of the coil. The current enters the coil by a spiral wire or ribbon below. The coil is wound with exceedingly fine wire on a very light rectangular frame and hangs between the poles, *N* and *S*, of the magnet. Usually there is a soft-iron cylinder in the space inside the moving frame to concentrate the magnetic lines of force. If a current is flowing through the coil, it acts like a tiny magnet with poles pointing to the front and rear, and tries to turn itself so that these poles may get as near as possible to the poles of the fixed magnet. The amount by which it is able to twist the suspension wire measures the current.

Fig. 343. Moving-coil galvanometer and diagram of essential parts.

304. The ammeter. The **commercial ammeter** is a *shunted, moving-coil galvanometer*. The instrument (Fig. 344) contains a coil of fine insulated copper wire, wound on a light frame, and mounted in jeweled bearings between the poles of a strong permanent horseshoe magnet. A fixed soft-iron cylinder midway between the poles of the magnet concentrates the field. The moving coil rotates in the gap between

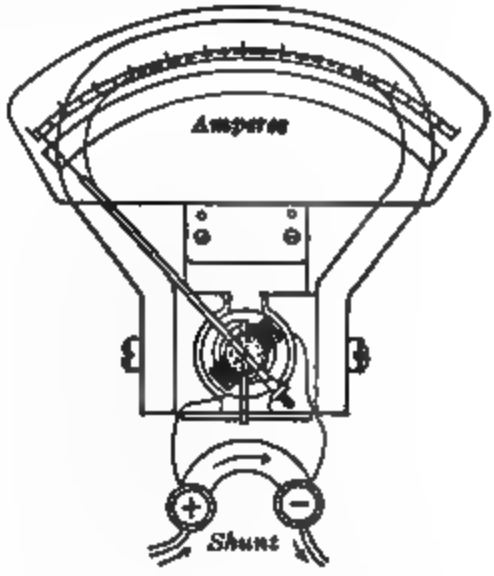

Fig. 344. Ammeter.

the core and the pole pieces. The coil is held in equilibrium by two spiral springs, which serve also to carry the current into and out of the coil. Only a small fraction, perhaps 0.001 of the current to be measured, goes through the movable coil, the major part being carried past the coil by a metal strip called a **shunt**. Since the current through the coil is a constant fraction of the whole current, the pointer which is attached to the moving coil can be made to indicate directly on a graduated scale the number of amperes in the total current.

It will be seen that the resistance of an ammeter, which is practically the resistance of the shunt, is very small, and that the whole current passes through the instrument.

Fig. 345. Voltmeter.

306. The voltmeter. The commercial **voltmeter** (Fig. 345) is simply a *galvanometer of very high resistance*. When electromotive force is applied to a galvanometer, the current it allows to pass is proportional to the voltage, and so the scale can be graduated to read the voltage directly.

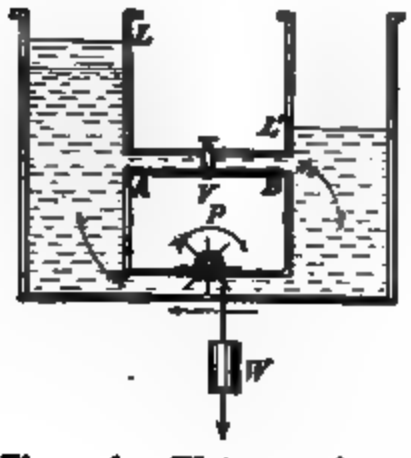

Fig. 346. Water analogue of voltmeter.

This will be understood by considering the water analogy shown in figure 346. It is evident that the current in the connecting pipe AB is a good measure of the difference in level between L and L', only when the current in AB is so small as not to change appreciably the levels whose difference is to be measured.

The instrument is usually a moving-coil galvanometer, like an ammeter. Indeed, the same instrument is often used for either purpose. A voltmeter does not have a shunt between its

terminals, like an ammeter, but it *does have a large resistance coil inserted in series*, so that only a very small current passes through the instrument, but all of it goes through the moving coil. In fact, such a voltmeter gives correct values only when the current used is so small as not to affect appreciably the voltage to be measured.

To make voltmeters usable over different ranges, we have merely to connect coils of different resistance in series with the same galvanometer.

Questions

1. An electromagnet is found to be too weak for the purpose intended. How may its strength be increased?

2. In looking at the N-end of an electromagnet, in which direction does the current go around the core, clockwise or counter-clockwise?

3. If you find that the N-pole of a compass needle held under a north and south trolley wire points toward the east, what is the direction of the current in the wire?

4. What is the difference in the construction of a relay and a sounder that makes it possible for a weak current to work one and not the other?

Practical Exercises

1. **Installing an electric bell at home.** Suppose you were asked to put in an electric bell. Plan the wiring and locations of the bell button and battery. Make a list of all the materials needed and the cost of each item. What do you estimate would be the expense of maintaining the battery?

2. **Trouble hunting in a bell circuit.** Suppose an electric bell in your home fails to ring. Tell just how you would locate and eliminate the trouble.

Electric Heating

306. Heating by electricity. We are familiar with the fact that electric cars are heated by electricity; we know that an electric-light bulb gets hot; and we may have used or seen electric

flatirons (Fig. 347), toasters, coffee percolators or radiators. But perhaps we do not realize that every electric current, however small, generates heat, since the heat is generated so slowly in an electric bell, telegraph, or telephone, that it is radiated off without raising the temperature of the wires appreciably. It is this heating effect, however, which limits the output of a generator; for if too heavy a current is drawn from the machine, the coils get so hot that the insulation is set on fire.

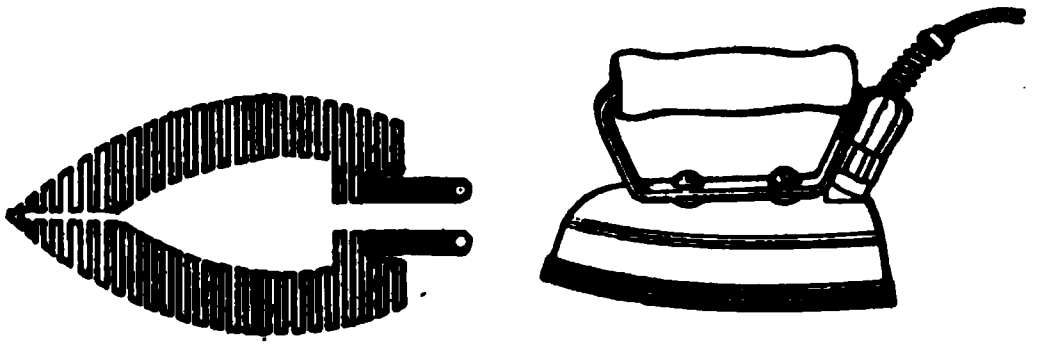

Fig. 347. Electric flatiron and heating coils.

307. Fuses and circuit breakers. To protect electrical machines from too much heat caused by excessive current, some sort of "electrical safety valve" has to be inserted in the circuit. Fuses are used for the small currents in house lights and small motors, and circuit breakers for larger currents in power stations. The essential part of a **fuse** is a strip of an alloy (Fig. 348*a*) which melts at such a low temperature that the melted metal can do no harm. The size of the fuse is such that if by accident too heavy a current is sent through the wires, the fuse melts and breaks the circuit. At the moment the fuse melts there is an arc across the gap which might set things on fire. So the fuse is commonly inclosed in an asbestos tube, as in the "cartridge fuse" (Fig. 348*b*); or in a porcelain cup which screws into a socket like a lamp, as in the "plug fuse" (Fig. 348*c*). When the fuse wire melts, it is said to "blow out."

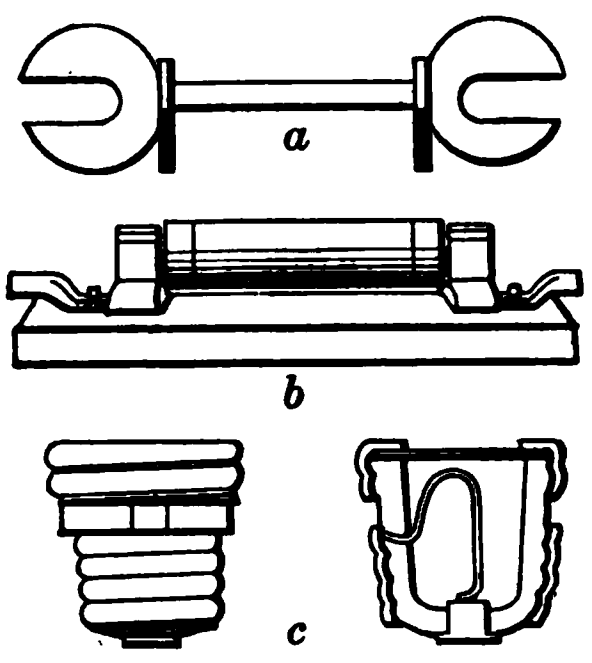

Fig. 348. Different types of fuses: (*a*) link; (*b*) cartridge: (*c*) plug.

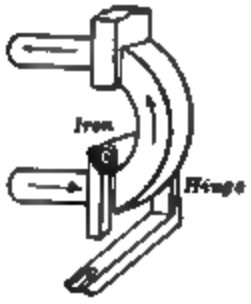

Fig. 349. Circuit breaker with diagram.

A circuit breaker (Fig. 349) is simply a large switch which is automatically opened by an electromagnet when the current is excessive.

Calculation of Electric Power

308. How electric power is measured. To measure water power, we must know the quantity of water flowing per minute and the " head " of the water. Thus

Water power = quantity of water per minute × head.

$$\text{H. P.} = \frac{\text{lb. per min.} \times \text{ft.}}{33{,}000}.$$

To measure electric power, we must multiply the quantity of electricity flowing per second — that is, the intensity of the electric current — by the voltage. Thus

Electric power = intensity of current × voltage.

The **watt** is the unit of electric power and may be defined as the power required to keep a current of **one ampere** flowing under a drop, or " head ", of **one volt.**

Watts = amperes × volts.

$$P = IE$$

where P = power in watts,

I = current in amperes,

E = e.m.f. in volts.

Since the watt is a very small unit of power, we commonly use the **kilowatt** (**kw.**), which is 1000 watts.

$$\text{Kilowatts} = \frac{\text{amperes} \times \text{volts}}{1000}.$$

For example, if a lamp draws 0.4 amperes from a 110-volt circuit, it is using power at the rate of 0.4 times 110, or 44 watts.

Again, suppose a street-car heater has a resistance of 110 ohms. At what rate is it consuming electricity on a 550-volt line? The current is $\frac{550}{110}$, or 5 amperes, and the power is 5 times 550, or 2750 watts, or 2.75 kw.

Whenever a current flows through a circuit, power is required to keep it flowing against the resistance of the circuit. This power is equal to the voltage measured between the terminals of the circuit multiplied by the current flowing in it, provided all the power expended in that part of the circuit is used in heating it.

That is, $P = EI$.

But according to Ohm's law $E = IR$

consequently, $P = IR \times I$ or I^2R.

Inasmuch as mechanical power is reckoned in horse power (h. p.), it will be convenient to know the relation of the unit of mechanical power to the unit of electrical power. Experiment shows that

1 horse power = 746 watts.

1 kilowatt (kw.) = 1.34 horse power (h. p.).

309. Electrical energy. Power means the rate of doing work, or *the rate of expenditure of energy. The total* ***work done****, or electrical energy expended, is equal to the* ***product*** *of the* ***rate*** *of doing work by the* ***time.*** Thus if a steam engine is working at the rate of 15 horse power for 8 hours, it does 8 times 15, or 120 **horse-power hours** of work. In a similar way, if an electric generator is delivering electricity at the rate of 15 kilowatts for 8 hours, it does 8 times 15, or 120 **kilowatt hours** of work.

For example, we buy electricity by the kilowatt hour. If the price is 10 cents per kilowatt hour, and if a store uses 100 lamps for 3 hours, each consuming electricity at the rate of 50 watts, it will cost

$$\frac{100 \times 3 \times 50 \times 0.10}{1000} = \$1.50.$$

310. The joule. In the laboratory we often find it convenient to use a smaller unit of energy, the **watt second, or joule.**

Energy (joules) = current (amperes) × e.m.f. (volts) × time (sec).

Or $$W = IEt.$$

The relation of the joule to other units of energy in common use is shown in the following table:

1 joule = 0.102 kilogram meters
= 0.738 foot pounds
= 0.238 gram calories.
1 B.t.u. = 1054 joules.

311. How much heat is generated by an electric current? The energy delivered to an electric heating coil, such as a flat-iron or soldering iron, is, as we have just seen, EI joules per second, or EIt joules in t seconds. But since Ohm's law tells us that $E = IR$, if there is no cell, generator, or motor in the part of the circuit considered, we have the alternative statement, which is often convenient in discussing electric heaters:

Energy turned into heat = I^2Rt (joules),

or, since a joule is about 0.24 calories,

$$H = 0.24\, I^2\, R\, t$$

where H = heat in calories,
I = current in amperes,
R = resistance in ohms,
t = time in seconds.

PROBLEMS

1. How much electrical power (watts) is required to light a room with 5 lamps, if each lamp draws 0.4 amperes from a 110-volt line?

2. A street-railway generator is delivering current to a trolley line at the rate of 1500 amperes and at 550 volts. At what rate (kilowatts) is it furnishing power?

3. A 10-kilowatt generator is working at full load. If the voltmeter reads 115 volts, how much does the ammeter read?

4. How many lamps, each of 120 ohms and requiring 1.1 amperes, can be lighted by a 25-kw. generator?

5. How much power is required by a laundry using 5 electric flatirons of 50 ohms each, connected in parallel on a 110-volt line?

6. How much will it cost at 10 cents per kilowatt hour to run a 220-volt motor for 10 hours, if the motor draws 25 amperes?

7. Would it be cheaper to buy the power needed in problem 6 at 8 cents per horse-power hour?

8. How much energy is consumed in a line whose resistance is 0.5 ohms, and which carries a current of 150 amperes for 10 hours?

9. How many joules of energy are consumed when a 40-watt lamp burns 10 minutes?

10. How many calories of heat are generated per hour in a 30-ohm electric flatiron using 4 amperes?

11. What is the cost of each calorie in problem 10, if the electricity costs 10 cents per kilowatt hour?

12. How much energy is turned into heat each hour by a current of 35 amperes in a wire of resistance 2 ohms?

13. If 88% of the energy received by an electric lamp is converted into heat, how many calories are developed in one hour by a 35-candle-power lamp drawing 0.9 amperes at 115 volts?

14. A 10-ohm coil of wire is used to heat 1000 grams of water from 15° C. to 75° C. in 10 minutes. How much current must be used?

PRACTICAL EXERCISE

Cost of operating various electric devices per hour. Bring to the school laboratory all the electric devices which you have at home, measure the power used by each, and then compare the costs.

ELECTRIC LIGHTING

312. Tungsten, or Mazda, lamps. The filament in modern incandescent lamps is pure metallic tungsten, which has an exceedingly high melting point, above 3000° C. This fine metallic wire is heated white hot, that is, to **incandescence**, by an electric current. The tungsten wire used in a 100-watt lamp is only about 3 mils (0.003″) in diameter; but it is so long that to

get it into an ordinary bulb it is wound zigzag on a star-shaped reel. The electricity is led into and out of the filament through two short wires (Fig. 350), which are melted into the wall of the bulb to prevent leakage of air and so must have the same coefficient of expansion as the glass. These wires are connected by copper wires to the brass collar and metal tip at the end of the bulb.

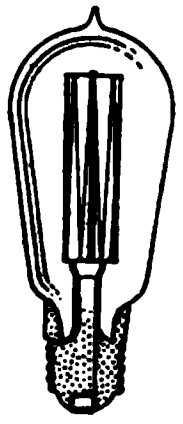

Fig. 350. Vacuum tungsten (Mazda B) lamp

313. Gas-filled tungsten lamps. Until recently it has been the practice of manufacturers to exhaust the bulbs of incandescent lamps (Mazda B) to an almost perfect vacuum, because the filament would burn up at once if there were any air present to support combustion. Experiments have shown, however, that in such lamps the filament slowly vaporizes, depositing a dark, mirror-like coating of metal upon the inside of the bulb, and so in another type (Mazda C) the bulb is filled with some inert gas, such as nitrogen or argon. The presence of an inert gas retards the evaporation of the filament and makes it possible to operate tungsten filaments at higher temperatures than in vacuum bulbs. The long filament in these lamps (Mazda C) is wound into an exceedingly fine spiral (Fig. 351) and mounted in a compact form to prevent its being cooled appreciably by the gas.

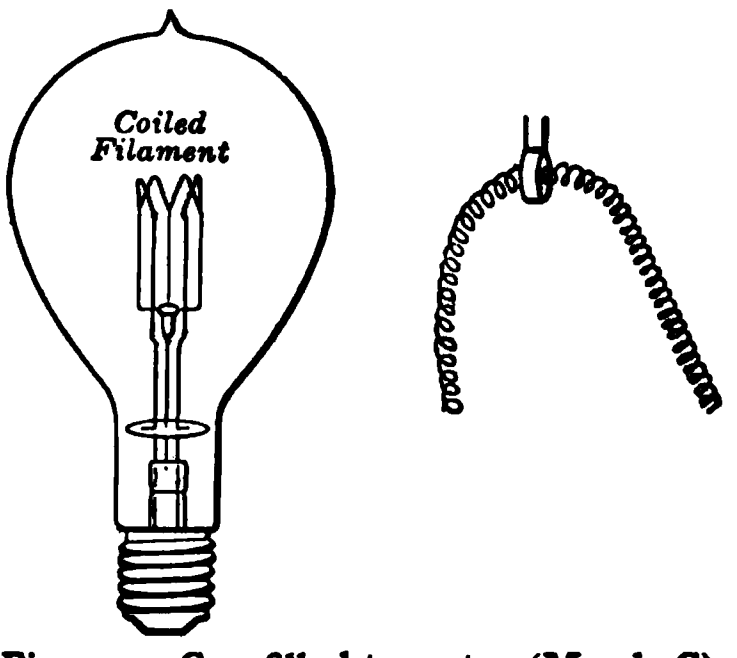

Fig. 351. Gas-filled tungsten (Mazda C) lamp with coiled filament.

314. Life and rating of incandescent lamps. Unless accidentally broken, Mazda lamps will easily last 1000 hours. Such lamps are usually grouped in parallel on a constant-potential circuit of from 110 to 120 volts. It is now the custom of manufacturers to rate all incandescent lamps in watts, and to specify on the label of every lamp the voltage at which it is designed to operate. During the past few years the

lamp manufacturers have repeatedly and rapidly increased the efficiency of the tungsten lamp. Such lamps are about three times as efficient as the old, now almost obsolete, carbon-filament lamps. The rate of consumption of electrical energy for a vacuum tungsten lamp is about 1.25 watts per candle power (section 427), depending on the size of the lamp. The rate for a gas-filled, 100-watt lamp for parallel circuits is less than 0.80 watts per candle power; and for a gas-filled series lamp for street lighting, the rate may be as low as 0.45 watts per candle power.

315. The electric arc. About a hundred years ago Sir Humphry Davy, by using a battery of 2000 cells, made an electric arc between rods of charcoal. This was merely a brilliant lecture experiment, and it was not until sixty years later, when practical generators had been built, that arc lights became commercially possible. It was soon found that the coke which is formed in the ovens of gas furnaces makes a more durable material for the carbon than wood charcoal.

To show the form of the electric arc, we may connect a circuit of 50 or more volts to two carbons, in series with a suitable rheostat. The light is so intense that the eyes must be shielded by blue glass from the direct glare. The arc can be projected on a screen with a convex lens. If direct current is used, the crater formed on the positive carbon and the cone on the negative carbon can be seen (Fig. 352). The great heat evolved is shown by the fact that iron wire can be melted in the arc.

Fig. 352. Positive and negative carbons of an arc.

Furnaces built on the principle of the electric arc are used to prepare artificial graphite, carborundum, calcium carbide, and various kinds of steel.

316. Modern arc lamps. Even coke carbon burns away, and so automatic lamps have been invented which feed their carbons gradually toward each other. Some of the early forms of these lamps made use of clockwork to feed the carbons;

but now it is common to use a clutch which is worked by an electromagnet. One form of this mechanism consists of a "ballasting" resistance B (Fig. 353), which opposes any increase or decrease of current between the carbon tips, and of a "regulating" coil S, to control the distance between the carbon tips. When there is no current, the plunger P drops and releases the friction clutch on the upper carbon C. When the current is on, the plunger P is pulled up and lifts the clutch and upper carbon the proper distance.

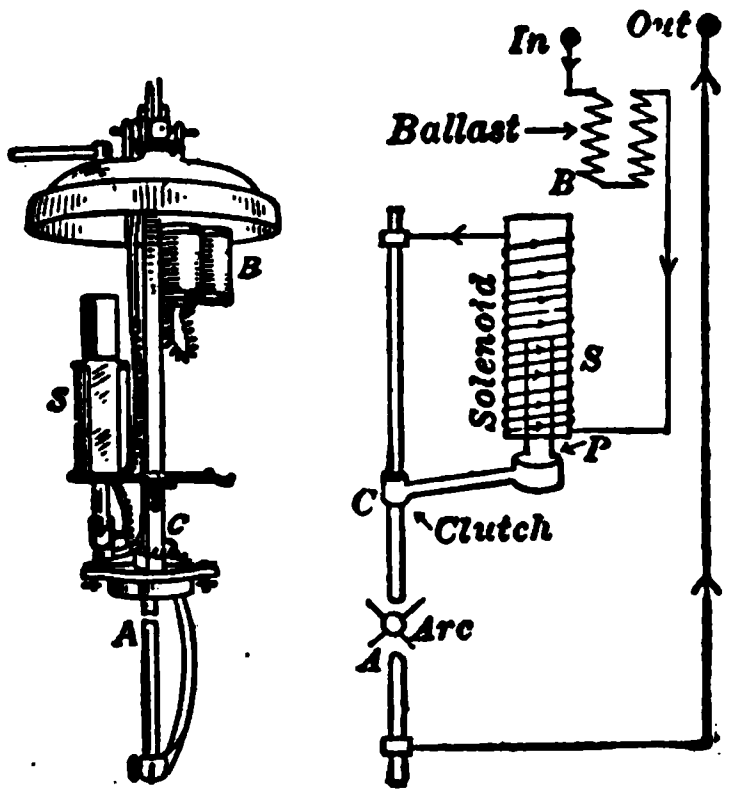

Fig. 353. Arc lamp, and diagram of automatic feed.

To overcome the rapid consumption of carbon rods, an **inclosed arc lamp** has come into use. When the arc is surrounded by a glass globe which is nearly air-tight, the available supply of oxygen is quickly used up and the same pair of carbons lasts 100 hours instead of only 7 or 8 hours.

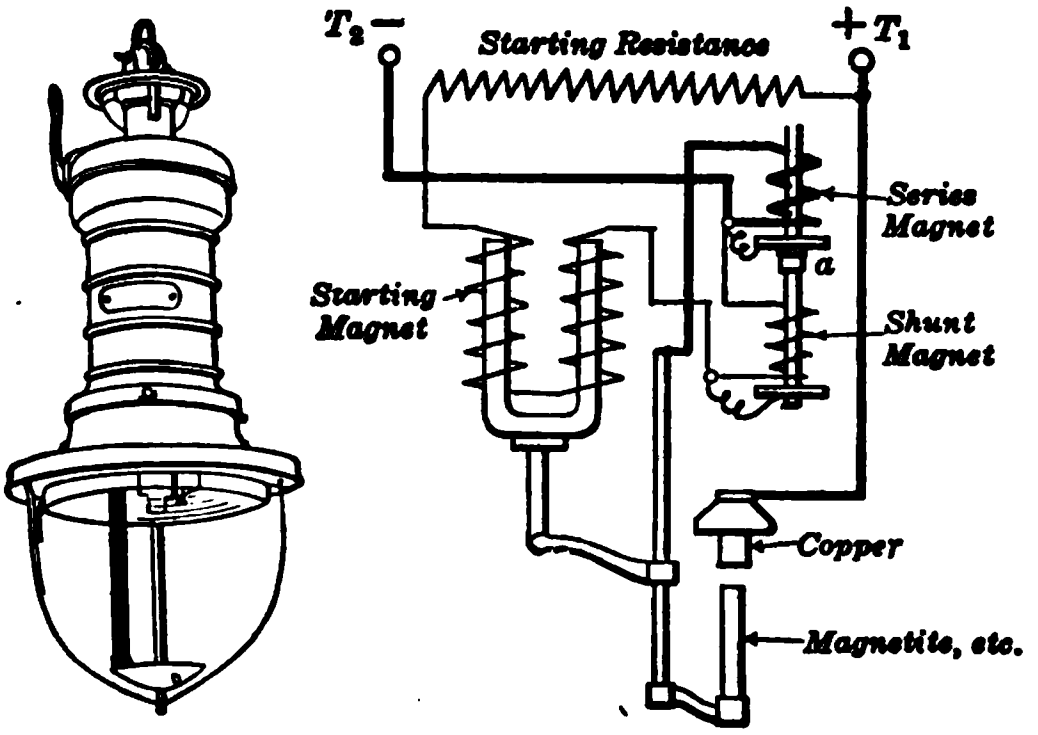

Fig. 354. Metallic arc lamp and diagram of connections.

One form of the flaming arc lamp is the **metallic, or magnetite, arc.** In this lamp (Fig. 354) the negative electrode is made of magnetite or some similar substance, powdered and compressed in a sheet-iron

tube; while the positive electrode is of solid copper, which wastes away very little. This lamp is used for street lighting on constant-current circuits.

If carbon rods are used with a core of calcium fluoride, the vapor given off is very luminous and emits light of a golden orange color. These **flaming arcs** are used on streets chiefly for display lighting. In this type the carbons are long and slender, and both carbons feed down.

In the **mercury arc**, or Cooper-Hewitt lamp, use is made of the luminescence of mercury vapor. The mercury is held in the lower end of a glass vacuum tube 2 to 4 feet long (Fig. 355). Some special device has to be used to start the current through the mercury vapor; but once started, the current flows easily through the hot vapor, which glows with a light composed of green, blue, and yellow, but *no red*. This gives a peculiar color to objects thus illuminated. (See Chapter XXII.)

Fig. 355. Mercury arc lamp, started by tilting.

Questions and Problems

1. In selecting the proper kind of electric lamp for illumination, what other factors must be considered besides watts per candle power?

2. How may a street car which is operated on a 550-volt line be lighted by 110-volt lamps? Draw a diagram of the connections.

3. How many 0.4-ampere lamps, connected in parallel, can be protected by a 20-ampere fuse?

4. How many candle power should a 50-watt tungsten lamp give, if it is rated as 1.2 watts per candle power?

5. The old-type, 16-candle-power carbon lamp required 55 watts. (*a*) Compute the watts per candle power. (*b*) If the lamp itself cost 16 cents, compute the total cost of burning it for 1000 hours.

6. A 25-watt Mazda B lamp is rated as 1.17 watts per candle power. If the lamp itself costs 27 cents and electricity costs 10 cents per kilowatt hour, compute (*a*) the candle power of the lamp, and (*b*) the total cost of burning the lamp for 1000 hours.

7. A gas jet burning 5 cubic feet of gas per hour gives a flame of 20 candle power. The gas costs $1.00 per 1000 cubic feet. A 40-watt lamp gives about 32 candle power. Electricity is 10 cents per kilowatt hour. Compare the cost of illumination with gas and electricity.

8. When gas is burned in a Welsbach mantle, it is generally consumed at the rate of 3.5 cubic feet per hour and gives about 70 candle power of light. Compare the cost of illumination with Welsbach mantles and electricity.

9. One hundred 25-watt 110-volt lamps are connected in parallel in a building which is located 200 feet from the generator. What size wire will be required, if the line drop in the main feeders is not to exceed 2 volts?

10. Why must a rheostat be used in series with the arc lamp in a projection lantern?

11. A small arc lamp needs a current of 5 amperes and an e.m.f. of 55 volts. What is the resistance of the lamp?

12. If the lamp in problem 11 is used on a 115-volt line, what resistance must be put in series with it?

13. A certain searchlight requires 100 amperes and a difference of potential of 60 volts. What resistance must be placed in series with it on a 110-volt circuit?

14. If the arc in problem 13 gives 128,000,000 candle power, how many candle power does it give per watt?

PRACTICAL EXERCISES

1. Report on the lighting system of your city. What sort of street lamps are used? What service is supplied for factories? What service is furnished for household uses? What is the method of distribution? How is your own home wired? Where is the meter located? How is the wiring protected by fuses?

2. Pocket flashlight. Take a pocket-flashlight lamp apart and examine its construction carefully. Make a clear diagram of the electrical circuit and explain its operation.

Chemical Effects of Electric Currents

317. Conduction by solutions. When an electric current flows along a copper wire, the wire becomes warm and is surrounded by a magnetic field. When an electric current flows through a solution of salt and water, the solution is warmed and is surrounded by the magnetic field; *and* it is at the same time **decomposed**, or broken up. For example, under certain conditions an electric current will decompose salt water into caustic soda, hydrogen, and chlorine. Not all liquids conduct electricity; thus alcohol and kerosene are nonconductors. All liquids which conduct electricity and are more or less decomposed in the process are called **electrolytes.**

318. Electrolysis of water. Water (made slightly acid with sulfuric acid) can be decomposed by an electric current in the apparatus shown in figure 356. The platinum electrodes are connected with a battery or generator, giving at least 5 or 6 volts. The electrode in tube *A*, which is connected to the positive (+) pole, is called the *anode;* and the other electrode in *B* is the *cathode.* The current passes through the solution from the anode to the cathode. Small bubbles of gas are seen to rise from both electrodes, and the gas collects in tube *B* twice as fast as in tube *A*. When tube *B* is full, we open the switch, and test the collected gases. To test the gas in tube *B*, we open the stopcock at the top and apply carefully a lighted match. This gas burns with a pale blue flame, which shows it to be *hydrogen.* If we open the stopcock in tube *A* and bring a glowing pine stick near, it bursts into a flame, which shows the gas to be *oxygen.*

Fig. 356. Water is decomposed by the electric current.

Thus we see that water is decomposed by electricity into its constituent elements, hydrogen and oxygen. This process of decomposing a compound by means of an electric current is called **electrolysis.**

319. Theory of electrolysis. The theory of this process may be stated as follows: The small quantity of sulfuric acid (H_2SO_4), when put into the water, breaks up into hydrogen ions ($2\,H^+$) and sulfate ions (SO_4^{--}), which have positive and negative charges of electricity respectively. When the current is sent through the solution, the positive hydrogen ions ($2H^+$) wander toward the cathode and the negative sulfate ions (SO_4^{--}) toward the anode. At the cathode, the hydrogen ions give up their positive charges and rise to the surface as bubbles of hydrogen. At the anode, the sulfate ions give up their negative charges of electricity and react with the water (H_2O) to form sulfuric acid (H_2SO_4) and to set free oxygen (O_2). In this way the sulfuric acid, which is added to conduct the electricity, is not used up, while the water ($2H_2O$) is broken into hydrogen ($2H_2$) and oxygen (O_2).

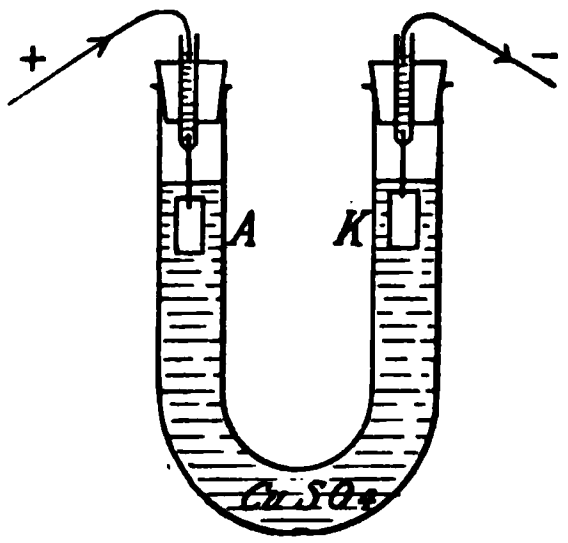

Fig. 357. Electrolysis of copper sulfate solution.

320. Electroplating. We may illustrate the process of electroplating by the following experiment.

We put two platinum electrodes in a U-tube filled with copper sulfate solution ($CuSO_4$), as shown in figure 357. After the electric current has passed through the solution for a few minutes, we find that the cathode is coated with metallic copper, while the anode is unchanged. If we reverse the direction of the current, we find that copper is deposited on the clean platinum plate, which is now the cathode, and that the copper coating on the anode gradually disappears.

In this way one metal can be coated with another. For example, articles of brass and iron, which corrode in the air, can be coated with nickel, which does not corrode. Similarly, much cheap jewelry is gold or silver plated. Many knives, forks, and spoons are silver plated, the best being what is called " triple " or " quadruple plate."

In practice the process is done in vats, as in figure 358. The objects to be plated are hung from one copper " bus " bar; and the metal to be deposited, in this case pure silver, is hung from the other bar. The vat contains a solution of the metal to be deposited. For silver plating a solution of silver and potassium cyanide is used. The

bar carrying the metal to be deposited is connected with the + terminal of a low-voltage generator, and the other bar to the − terminal. The silver anodes dissolve as fast as the silver is deposited on the cathode, the strength of the solution remaining unchanged. When the coating has reached the proper thickness, a final process of buffing and polishing gives the surface the desired appearance.

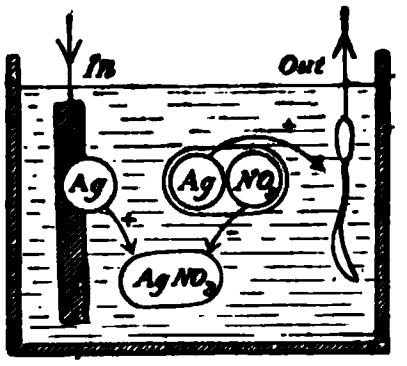

Fig. 358. Diagram of electroplating vat.

321. Electrotyping. One might suppose that this book was printed from the actual type which was set up; but that is not the case. Most books which are made in large numbers are printed from electrotype "plates." A wax impression of the page as set up in type is made in such a way that every letter leaves its imprint on the wax mold. Since the wax is itself a nonconductor, it has to be coated with graphite. This mold is then placed in a solution of copper sulfate and attached to the negative bus bar, so that it becomes the cathode, while a copper plate acts as the anode. After the current has deposited copper on the wax mold to the thickness of a visiting card, this shell of copper is separated from the mold and "backed up" with type metal to give it the necessary strength for printing.

322. Refining of metals. Copper as it comes from the smelting works is not pure enough for some purposes, such as making wires and cables for carrying electricity. So the copper for electrical machinery is refined by electricity. The crude copper is the anode, a thin sheet of pure copper is the cathode, and the solution is copper sulfate. The copper deposited by the electric current is remarkably pure. The anode of crude copper gradually dissolves, and the impurities drop to the bottom of the vat as mud. In this mud there is generally enough gold and silver to pay the expense of the process. The crude copper which comes from ordinary smelters with from two to five per cent of impurities is refined by electrolysis so that it is about 99.95 per cent pure copper. Copper purified in this way is known commercially as **electrolytic copper.**

323. Electrochemical equivalents of metals. Experiments show that a given current always deposits the same amount of a given metal from a solution in a given time. In fact, this is so accurately true that it is the basis of the most accurate method known for calibrating standard ammeters. The amount of metal deposited by a current depends (1) on the strength of the current, (2) on the time it flows, and (3) on the nature of the metal. The definite quantity of a substance deposited per hour by electrolysis when one ampere is flowing through a solution is called the **electrochemical equivalent** of the substance.

ELECTROCHEMICAL EQUIVALENTS

ELEMENT	SYMBOL	GRAMS PER AMPERE HOUR
Aluminum	Al	0.337
Copper	Cu	1.186
Gold	Au	3.677
Hydrogen	H	0.0376
Nickel	Ni	1.094
Oxygen	O	0.298
Silver	Ag	4.025

324. Definition of the international ampere. Electrical engineers have agreed to define the ampere in terms of its chemical effect. If two silver (Ag) plates are placed in a jar of silver nitrate solution ($AgNO_3$), and if the + and − terminals of a battery are connected, one to one plate and one to the other, it will be found that the plate where the current goes *in* (the **anode**) loses in weight because silver is dissolved, and the plate where the current comes *out* (the **cathode**) gains in weight because silver is deposited. *By international agreement the quantity of electricity which deposits 0.001118 grams of silver is* ***one coulomb****; and the current which deposits silver at the rate of 0.001118 grams per second is* ***one ampere****.* The apparatus used in the accurate measurement of current by this method is shown in figure 359. The anode is the silver disk S at the left, and the cathode is the silver (or platinum) cup P at the bottom. The porous cup C at the right is put into the solution between the anode and the cathode to catch any mud or slime due to impurities in the anode.

Questions and Problems

1. To determine which is the + and which the − pole of a generator, two copper wires are sometimes connected to the terminals and the bared ends dipped in a glass of water. One will soon turn dark. How does this experiment show which is the positive terminal?

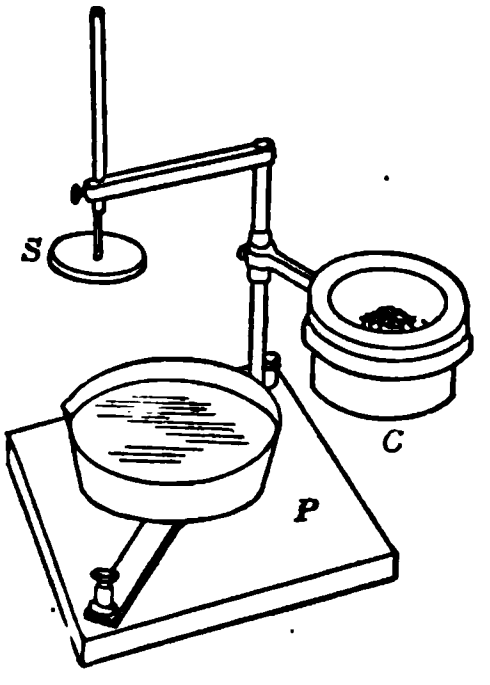

Fig. 359. Silver coulombmeter.

2. How many grams of silver are deposited in 8 hours from a silver nitrate solution by a current of 5 amperes?

3. How many liters of hydrogen will be generated by a current of 10 amperes in 4 hours? (A liter of hydrogen weighs 0.09 grams under standard conditions.)

4. How many amperes will be needed to deposit 1.5 pounds of copper per day of 24 hours?

5. How long will it take a current of 200 amperes to refine a ton of copper?

6. In an electroplating bath how many grams of zinc will be deposited by a current of 15 amperes in 45 minutes?

7. In calibrating an ammeter the current was allowed to run 2 hours and 15 minutes, and deposited 39.5 grams of silver. What would be the reading of the ammeter, if correct?

8. Two electroplating vats are arranged in series, one for gold and the other for silver. How much gold is deposited while 1 gram of silver is being deposited?

9. An electroplater buys his electricity by the kilowatt hour. The metal deposited in electroplating is proportional to the number of ampere hours. Why does he use as low a voltage as possible?

10. What is meant by triple and quadruple plate?

11. An iron casting is to be copper plated and then nickel plated. If the current used in each case is 10 amperes, how long must it remain in each vat to have 8 ounces of each metal deposited on it? (1 ounce = 28.35 grams.)

Practical Exercise

Cleaning silver by the electrolytic method. Fill an aluminum pan with a hot solution of baking soda and salt (about 1 teaspoonful of

each to a quart of water). Place the tarnished silver in the solution so that it is entirely covered. Keep the solution boiling a few minutes until the tarnish has been removed. Rinse the silver in clean water and wipe with a soft cloth. For an explanation of the chemical action involved, read page 432 *Black and Conant's* Practical Chemistry (Macmillan). This method does not apply to plated ware.

Storage Batteries

325. What is a storage battery? Some people think of a storage battery as a sort of condenser where electricity is stored; but it is not that. In the storage battery, as in any other battery, the electrical energy comes from the chemical energy in the cells. The **charging** process consists in forming certain chemical substances by passing electricity through a solution, just as hydrogen and oxygen are formed in the electrolysis of water. In the **discharging** process, electricity is produced by the chemical action of the substances which have been formed in the charging process.

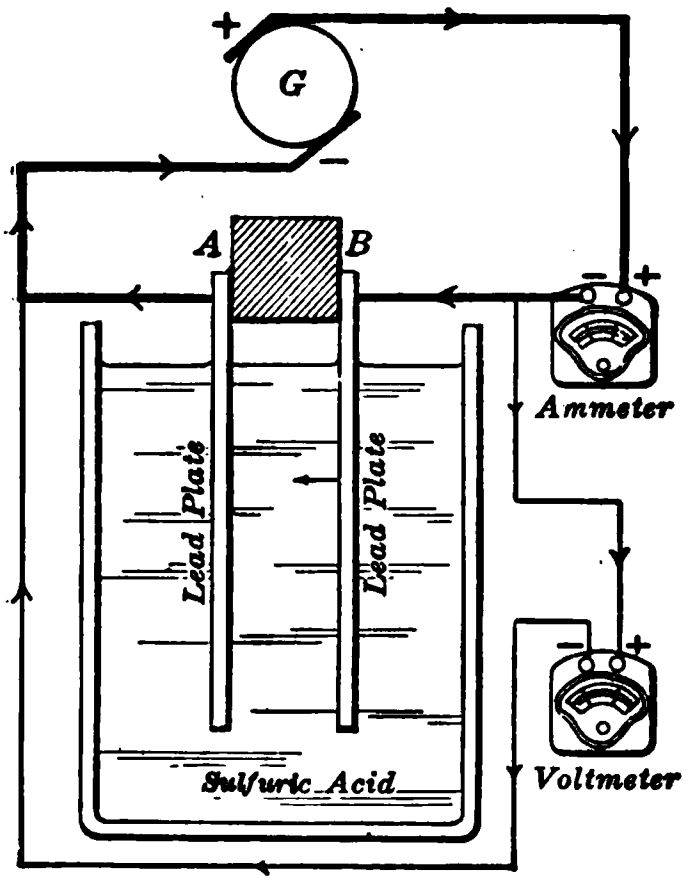

Fig. 360. Forming a lead storage cell.

326. Lead storage cell. We may make a small lead storage cell by putting two sheets of ordinary lead in a glass battery jar with a very dilute solution of sulfuric acid. To charge it or "form" the plates quickly, we connect this cell and an ammeter in series with a battery of three or more cells; or better, a generator of about 6 volts (Fig. 360). While the current is passing, bubbles of gas rise from each plate. If, after a few minutes, we disconnect the generator and touch the wires of a voltmeter to the lead terminals, it shows an e.m.f. of about 2 volts. If we then connect an electric bell in series with the ammeter and the lead cell, the bell rings. This indicates that a current is produced; and the ammeter shows that the current on discharge is opposite to that used in charging the cell.

When the plates are lifted out of the solution after charging, plate *B*, the anode, is *brown*, because of a coating of lead peroxide (PbO_2); and plate *A*, the cathode, is the usual gray of pure lead (Pb).

In the commercial lead storage cell (Fig. 361), the negative plates are pure spongy lead (Pb), the positive are lead peroxide (PbO_2), and the electrolyte is dilute sulfuric acid. In the charging process, the positive plate, which is dark brown, is coated with lead peroxide, and the negative, which is gray, is made into spongy lead. In the discharging process, both plates gradually return to a condition where each is covered with lead sulfate ($PbSO_4$). The chemistry of these changes can be briefly described by the following equation:

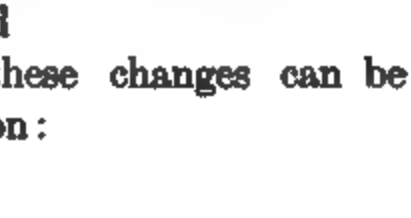

Fig. 361. Glass jar of a storage cell supported on sand.

$$PbO_2 + Pb + 2\,H_2SO_4 \underset{\text{Discharge}\longrightarrow}{\overset{\longleftarrow\text{Charge}}{=}} 2\,PbSO_4 + 2\,H_2O.$$

It will be noticed that during the charging process the acid becomes more concentrated. So the condition of a storage cell can be determined by the specific gravity of the acid. The plates in the commercial lead battery are either roughened and then changed into the proper active materials, lead peroxide and spongy lead, by a chemical process, or are punched full of holes which are filled with the active material.

327. Uses of the storage battery. The most familiar form of storage battery is doubtless that used on automobiles for starting, lighting, and ignition. Such a battery (Fig. 362) usually consists of 3 cells (6 volts) or 6 cells (12 volts), and has a capacity of from 60 to 80 ampere hours (see section 328). Since the majority of automobile owners are careless about giving the battery, which is the heart and

center of the starting and lighting system, the attention it should have, these batteries have to be built for abuse as well as for use.

Very large storage batteries are used in connection with central power stations to regulate the load by helping to carry the "peak" loads, and to serve as reserve power to be used in case of emergency. Large storage batteries are used on submarine boats; for while the boat is submerged, it is wholly dependent for power on its batteries.

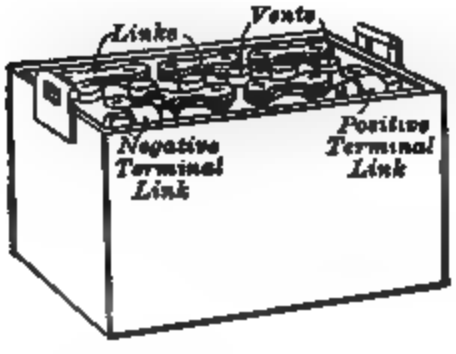

Fig. 362. Automobile battery and section of one cell.

Storage batteries are also used for train lighting and are in this case charged from an axle-driven generator. There is a rapidly growing field of usefulness for the storage battery in vehicle service, both for pleasure carriages and for heavy trucks.

There are many other important uses of the storage battery, in radio telegraphy and radio telephony, for private lighting plants where the service of a central station is not available, for telephone exchanges and telegraph circuits, for fire-alarm and signal systems, and in testing laboratories where a constant voltage is necessary.

328. Testing a battery. As yet no one has invented a "fool-proof" storage battery. It requires continual, intelligent oversight, just like any other delicate piece of machinery. We may test a dry cell very easily with a pocket ammeter; but if we try the same method with a storage battery, *we instantly burn out the instrument.* This happens because the internal resistance of the battery is exceedingly small, and accordingly the current which flows through the ammeter is enormous.

The voltage of a storage cell is about 2 volts. Nevertheless it should be remembered that *the voltage of a cell on open circuit tells us absolutely nothing about its condition as to charge and discharge.* The voltage must always be measured during the process of charging or discharging at its normal rate. Cells may be fully charged up to about 2.5 volts. The discharge should be stopped when the terminal voltage has dropped to about 1.8 volts at normal rate of discharge. Storage cells are sold according to their **capacity in ampere hours**, and this rating is based on a steady discharge for 8 hours. Thus, an 80-ampere-hour battery would maintain a current of 10 amperes for 8 hours, and so 10 amperes would be its normal rate of discharge.

The amount of charge in a battery is best determined by measuring the specific gravity of the electrolyte by means of a ***hydrometer.*** The specific gravity of the acid used depends on the type of battery and its intended service. For portable automobile batteries, the solution should have a specific gravity of 1.27 to 1.29 when fully charged, and it will be from 1.15 to 1.17 when completely discharged. The manufacturers furnish careful directions for the use and care of their batteries.

329. Care of a battery. Among the most important points to bear in mind are the following:

(1) Test each cell with a hydrometer every two weeks.

(2) Keep the plates covered with liquid. Add only distilled water.

(3) In charging, connect the positive terminal of the power supply to the + terminal of the battery, and use only direct current.

(4) Do not short-circuit the terminals of a battery.

(5) Keep all connections clean and bright.

(6) An idle battery will not remain charged, but must have attention at least once a month.

330. Edison storage battery. The great objections to the lead storage battery are its weight, its expense, and its need of close supervision. Edison has invented a storage cell in which the negative plate is pure iron in a steel frame, the positive plate is nickel peroxide, and the solution is caustic soda.

If a current is drawn from this battery (Fig. 363), the nickel peroxide (NiO_2) is reduced to a lower oxide (Ni_2O_3), while the iron is oxidized to form F_2O. This action is reversed on charging, as will be seen in the following chemical equation:

$$\xleftarrow{\text{Charge}}$$
$$2\,NiO_2 + Fe = Ni_2O_3 + FeO$$
$$\xrightarrow{\text{Discharge}}$$

It will be noted that the electrolyte does not appear in this equation at all. The change in its density is therefore so slight that it is insufficient to indicate the condition of the cell.

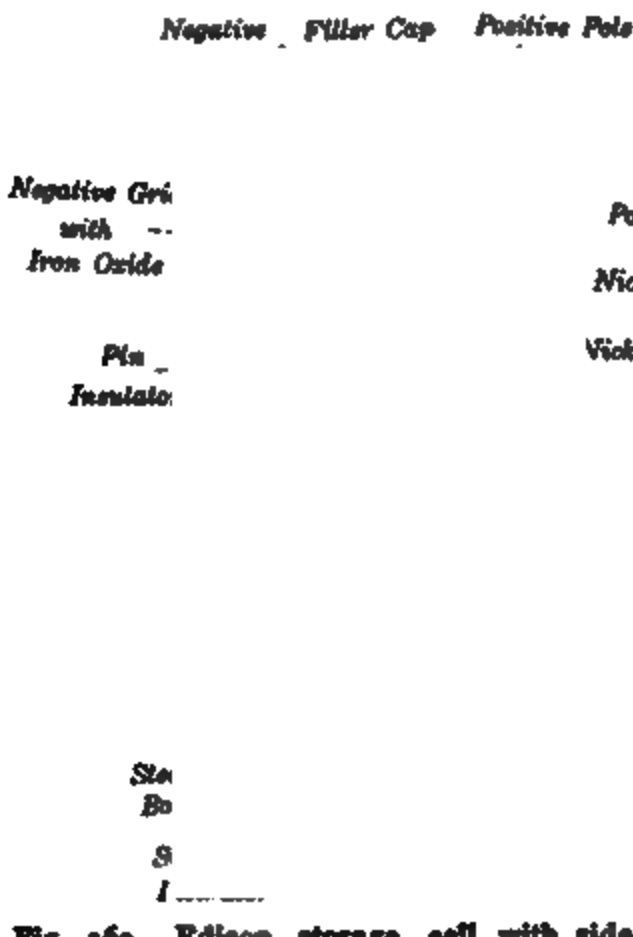

Fig. 363. Edison storage cell with side partly cut away to show construction.

Since this cell is intended for traction work, great pains have been taken to make it light, strong, and compact. Instead of being placed in a glass or hard-rubber tank, it has a thin nickel-plated, sheet-steel case. In a lead cell the normal voltage on discharge is 2 volts; in the Edison cell it is 1.2 volts. For the same capacity of output, the Edison cell is about half as heavy as the lead cell. As the internal resistance of the Edison is a little more than that of the lead cell, its efficiency is a little lower.

Problems

1. A lead cell has an e.m.f. of 2.00 volts, and its internal resistance is 0.004 ohms. What will be its terminal voltage when discharging 25 amperes?

2. What would be the impressed voltage needed to charge the cell of problem 1 at the rate of 25 amperes?

3. What would be the terminal voltage of the cell in problem 1 when discharging at the rate of 50 amperes?

4. If the e.m.f. of a lead cell is 2.3 volts on open circuit, while the terminal voltage when the cell is delivering 10 amperes is only 2 volts, what is the internal resistance of the cell?

5. A battery of 24 lead storage cells in series, each having an e.m.f. of 2.1 volts, a normal charging rate of 15 amperes, and an internal resistance of 0.005 ohms, is to be charged by a generator. What must be the terminal voltage of the generator?

6. In a trolley system the generator maintains 565 volts on the line. How many lead storage cells in series, each of 2.1 volts, will be needed to help the generator carry the peak of the load?

7. Most manufacturers of lead cells allow about 55 ampere hours for each square foot of positive plate area. How large a plate area will be required in problem 2?

8. A storage battery is used to light 20 incandescent lamps, each requiring 0.4 amperes at 112 volts. How many cells, each having an e.m.f. of 2 volts and an internal resistance of 0.004 ohms, will be needed?

9. How many Edison storage cells of type B-2 are needed to light 10 incandescent lamps which are connected in parallel? Each lamp requires 0.4 amperes. This type of cell has a capacity of 40 ampere hours when discharging at its normal rate of 7.5 amperes and gives 1.2 volts per cell at this discharge rate.

Practical Exercise

Report on a storage-battery service station. Visit a service station in your neighborhood and find out how cells are charged, and how their condition is tested. Describe all the instruments used. Examine a "sick" battery which has been taken apart. Why is the life of an automobile storage battery so short?

SUMMARY OF PRINCIPLES IN CHAPTER XVI

Lines of magnetic force around a straight current are concentric circles.

Thumb rule for *straight wire:* use *right* hand. *Thumb* points with current. *Fingers* curl with magnetic flux.

Lines of force around a coil mostly go through inside and come back outside.

Thumb rule for *coil:* use *right* hand. *Thumb* points toward N-pole. *Fingers* curl with *current*.

Power delivered to circuit = intensity of current × voltage.

Watts = amperes × volts.

1 horsepower = 746 watts.

Electrical energy is measured commercially in kilowatt hours: equals kilowatts × hours.

Power used to *overcome resistance*

= current squared × resistance.

Watts = (amperes)^2 × ohms.

Joule is a watt second.

$$\text{Energy in joules} = I^2Rt$$

$$\text{Heat in calories} = 0.24\ I^2Rt$$

Weight of a substance deposited by a current = electrochemical equivalent × current × time.

Lead storage cells: *Positive* plate, lead peroxide; *electrolyte*, sulfuric acid; *negative* plate, spongy lead.

Action on charge and discharge:

$$\xleftarrow{\text{Charge}}$$

$$PbO_2 + 2\ H_2SO_4 + Pb = 2\ PbSO_4 + 2\ H_2O.$$

$$\xrightarrow{\text{Discharge}}$$

Edison storage cell: *Positive* plate, nickel peroxide; *electrolyte*, solution of caustic soda; *negative* plate, iron.

Action on charge and discharge:

$$\xleftarrow{\text{Charge}}$$

$$2\ NiO_2 + Fe = Ni_2O_3 + FeO.$$

$$\xrightarrow{\text{Discharge}}$$

Questions

1. Is the magnetism created by an electric current in any way different from the magnetism of a magnetized steel bar?

2. Why is an ammeter more likely to be injured than a voltmeter?

3. Why do we test a dry cell with a 30-ampere ammeter but do not so test a storage battery?

4. Why does a test with an ammeter give a better indication of the condition of a used dry cell than a test with a voltmeter?

5. Which will yield more heat for warming an electric car, a 50-ohm resistance connected across a 50-volt line, or a 100-ohm resistance connected across a 100-volt line?

6. Compare the cost per hour of running a 55-ohm electric heater on a 55-volt circuit and on a 110-volt circuit, if power costs 10 cents per kilowatt hour.

7. If electricity is more expensive than gas for lighting, why is electricity so commonly used?

8. Why can you not charge a lead storage cell from a dry cell?

9. What is the advantage of electrotype plates over the original type in printing a book?

10. How would you test the state of charge or discharge of an Edison cell?

11. What precautions must be taken in using an electric flatiron?

12. If the current on a given line is doubled, how is the power loss due to heat increased?

13. Make a list of ten "Don'ts" in the use and care of a lead storage battery.

CHAPTER XVII

INDUCED CURRENTS

Currents induced by magnets — Lenz's law.

The generator — wire cutting lines of magnetic force — amount and direction of induced e.m.f. — Fleming's rule — revolving loop — commutator — Gramme ring and drum armatures — field excitation.

The motor — side push on wire carrying current — motor rule for direction of push — forms of commercial motors — back e.m.f. — starting box — applications — efficiency.

Other applications of induced currents — induction by electromagnets — induction coils — automobile ignition — self-induction — make-and-break spark coils — the telephone.

331. Faraday's discovery. If we had to depend on batteries for all of our electric currents, we should not be lighting our streets and houses with electric lamps or riding on electric cars. The cost of zinc as a fuel in the voltaic cell makes the battery too expensive as a source of large quantities of electricity.

About 1831, both Faraday and Henry discovered that it is possible to transform mechanical energy directly into electrical energy. Their method of producing electric currents by means of magnets is the underlying principle of the commercial generator, which has made possible the modern age of electricity.

332. Current induced by magnets. If we connect the ends of a coil of many turns of fine insulated wire to a lecture-table galvanometer, and then quickly move the coil down over one pole of a strong horseshoe magnet, as shown in figure 364, we observe a deflection. When we again raise the coil, we observe a deflection in the opposite direction. If we now lower the

Fig. 364. A coil moving downward in a magnetic field generates a current as shown.

coil and hold it down, we find that the galvanometer pointer comes back to zero. If we repeat the experiment, moving the coil down slowly and up slowly, we find that the deflection is less than before.

Such experiments show that it is possible to produce momentary electric currents without a battery. An electric current produced by moving a coil in a magnetic field is called an **induced current.** It is evident from the experiment that the current is induced only when the wire is **moving** and that the direction of the current is reversed when the motion changes direction. Since an electric current is always made to flow by an electromotive force, the motion of a coil in a magnetic field must generate an **induced electromotive force.**

333. Direction of induced currents. If we take the same apparatus (Fig. 364) and move the coil down over the *N*-pole of the magnet and then down over the *S*-pole, we find that the deflections are in opposite directions in the two cases. To determine in which direction the induced current is flowing in the coil, one may make a little voltaic cell by putting in one's mouth a copper wire and a zinc wire connected to the galvanometer. Since we know that the copper is the positive electrode, we can compare the direction of the galvanometer deflection caused by the cell current with that caused by the induced current, and so determine the direction of the latter. In this way we find that when the coil is moving down over the *N*-pole of the magnet, the induced current is in such a direction that the lower face of the coil is an *N*-pole. In a similar way we find that when the coil is brought down over the *S*-pole of the magnet, the induced current is in such a direction that the lower face of the coil is an *S*-pole. In both cases the lower face of the coil is a pole of such a sort as to be repelled by the pole toward which it is moving.

The direction of induced currents may be stated as follows: *An induced current has such a direction that its magnetic action tends to resist the motion by which it is produced.* This is known as **Lenz's law.**

THE GENERATOR

334. The importance of the generator. The most useful application of induced currents did not come until nearly forty years after Faraday and Henry made their wonderful

discovery. Then the generator was developed, by means of which the enormous energy of steam engines and water wheels can be transformed into electricity. The electricity generated in this way can be transmitted many miles. It can be used in motors to turn all sorts of machinery, in lamps of various kinds to light our streets and homes, in heaters to warm cars and sometimes houses, and in furnaces to melt iron and steel. Thus the generator has revolutionized modern industry by furnishing cheap electricity.

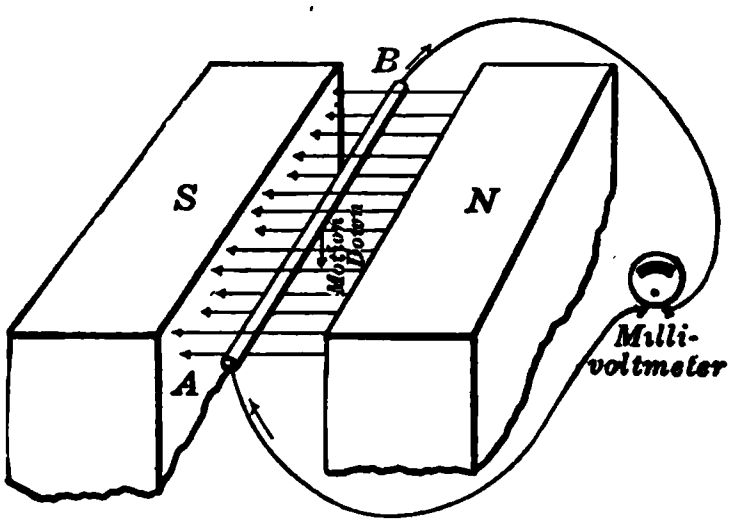

Fig. 365. Induced e.m.f. in a wire cutting lines of force.

335. Wire cutting lines of magnetic force. A simple way to get at the fundamental idea of the generator is to think, as Faraday did, of the induced e.m.f. produced in a *single wire when it is moved across a magnetic field.* Suppose the straight wire AB is pushed down across the magnetic field shown in figure 365. An induced e.m.f. is set up in AB, which makes B of higher potential than A, as can be shown by connecting B and A with a voltmeter. As long as the wire remains stationary no current flows. Even if the wire does move, if it be in a direction parallel to the lines of force, no current flows. In short, a wire must *move so as to cut lines of magnetic force,* in order to have an e.m.f. induced in it.

336. Direction of induced e.m.f. We have just seen that when the wire AB in figure 365 is moved down, the induced current *in* it is from A to B. If the wire were moved up, the induced current would be from B to A. Furthermore, if the field is reversed without changing the direction of motion of the wire, the current reverses. It will be seen, then, that the direction of the induced e.m.f. depends upon two factors, (*a*) the direction of the motion of the wire, and (*b*) the direction of the flux, or magnetic lines of force. The relation of these three

directions may be kept in mind by Fleming's rule of three fingers, as shown in figure 366.

FLEMING'S RULE. *Extend the thumb, forefinger, and center finger of the right hand so as to form right angles with each other. If the* ***thumb*** *points in the direction of the* ***motion*** *of the wire, and the* ***forefinger*** *in the direction of the magnetic* ***flux****, the* ***center*** *finger will point in the direction of the induced* ***current.***

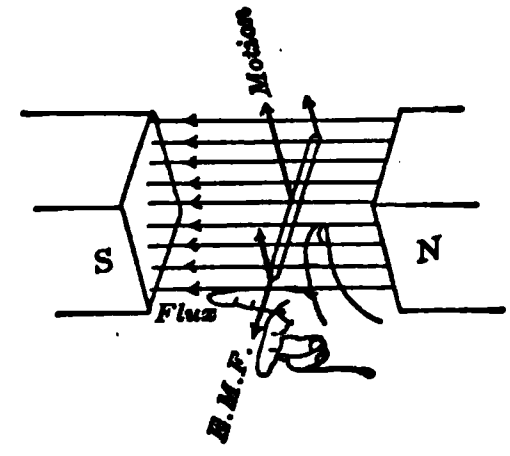

Fig. 366. Right-hand rule for induced e.m.f.

To remember this rule, notice the corresponding initial letters in the words "fore" and "flux," "center" and "current."

337. Amount of induced e.m.f. If we have a large electromagnet with flat-faced pole pieces (Fig. 367), we can demonstrate the various laws about induced currents in a conductor. If we move a wire down through the gap between the pole pieces, a millivoltmeter will show the induced current. If we hold the wire at rest in the gap, we observe no current. If we move the wire horizontally, parallel to the lines of magnetic flux, we get no current. If we move the wire up through the gap, we observe a current in the opposite direction, as predicted by Fleming's rule. If we increase the magnetic field by increasing the current through the electromagnet, we increase the induced current. If we move the wire more quickly through the gap, we increase the induced current. Finally, if we bend the wire into a loop of several turns, and move the loop down over one pole so that all the wires on one side of the loop pass through the gap, we find that the current is increased.

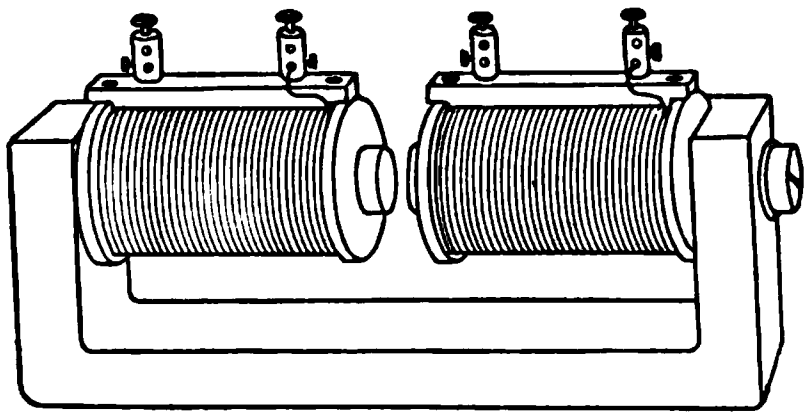

Fig. 367. Electromagnet for demonstrating induced e.m.f.

In this experiment we see that the induced e.m.f. is increased by moving the wire faster across the magnetic field, by making the magnetic field stronger, and by using more

turns of wire. In short, *the amount of induced e.m.f. depends on three factors:* (1) *the speed;* (2) *the magnetic field; and* (3) *the number of turns.*

Induced e.m.f. varies as *speed* × *flux* × *turns.*

338. Commercial generators. A machine for converting mechanical energy into electrical energy is called a **generator.** Its essential parts are two: (1) the **magnetic field,** which is produced by permanent magnets, as in the magneto, or by electromagnets, as in larger generators, and (2) a **moving coil** of copper wire, called the **armature,** wound on a revolving iron ring or drum. The armature wires correspond to the moving wires in the experiments above.

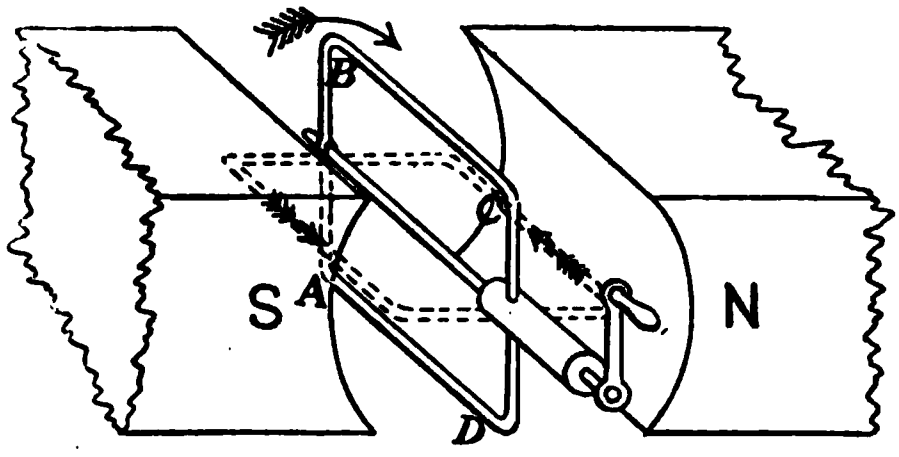

Fig. 368. Single loop of wire turning in a magnetic field.

339. Current in a revolving loop of wire. If we rotate a rectangular coil between the poles of a large horseshoe magnet, or better, of an electromagnet, we can detect an electric current in the revolving coil by connecting it with flexible leads to a galvanometer. As we turn the coil, the current is reversed every half-revolution.

It will help us to understand just what is happening in the revolving coil if we first consider what would happen in a single loop of wire which is rotated in a magnetic field, as shown in figure 368. If we start with the plane of the loop vertical and turn the handle in a clockwise direction, the wire BC moves *down* during the first half-turn; and so, by Fleming's rule, we should expect the induced e.m.f. to tend to send the current from C to B. At the same time the wire AD is moving *up,* and the current will tend to flow from A to D. The result is that during the first half-turn the current goes around the loop in the direction $ADCB$. During the second half-turn the current is reversed and goes around in the direction $ABCD$.

To prove that this really does happen in the loop, we can cut the wire and connect the ends to *slip rings* x and y, as in figure 369. The brushes B' and B'', which rest on the rings, are connected to a milliammeter. In this way it can be shown that

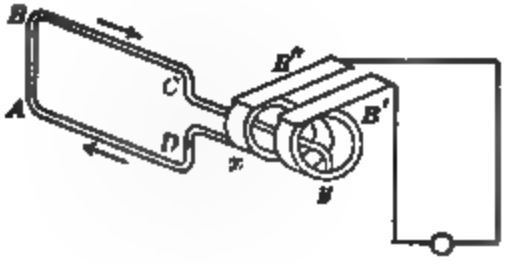

Fig. 369. Coil rotating between poles of electromagnet, and diagram of single loop connected to slip rings.

there is generated in the coil an **alternating current** which reverses its direction twice in every revolution. Moreover, it is possible to show that the induced e.m.f. starting at zero goes up to a maximum and then back to zero in the first half-turn; then it reverses and goes to a maximum in the opposite direction, and finally back to zero. The induced e.m.f. reaches its maximum when the coil is horizontal, because in this position the wires AD and BC are cutting lines of force most rapidly. This is illustrated by the curve in figure 370. A complete revolution of the loop (360°) makes a curve, including a maximum in one direction *and* the following maximum in the opposite direction. This is called a **cycle** of current.

Fig. 370. Curve to show relation of induced e.m.f. to position of loop.

Machines which are built to deliver alternating currents are called **alternating-current (a-c.) generators** or **alternators.**

340. Commutator. To get a **direct current**, that is, one which flows always in the same direction, we have to use a **commutator.** To understand how this works, let us study a very simple case. If the ends of the loop in section 339 are connected to a **split ring**, as shown in figure 371, we may set the brushes $B+$ and $B-$ on opposite sides of the ring, so that each brush will connect first with one end of the loop and then with the other. By properly adjusting the brushes, so that they shift sections on the commutator just when the current reverses in the loop, that is, when the loop is in a vertical position, we may get the current to flow only *out* at one brush $B+$, and only *in* at the other brush $B-$. The direction of the current in the external circuit is always the same, even though the current in the loop itself reverses twice in every revolution.

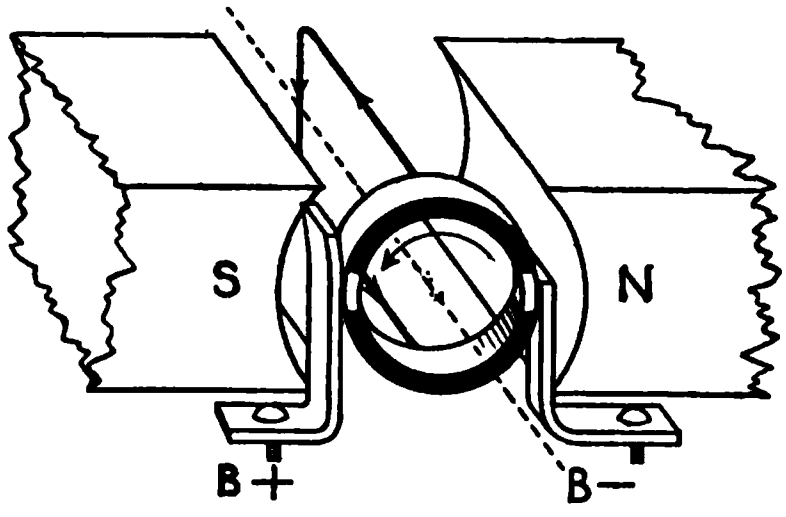

Fig. 371. Split-ring commutator.

The current delivered by such a machine can be represented by the curve in figure 372. Although it is always in the same direction, it is pulsating.

A machine with a commutator for delivering direct current is called a **direct-current (d-c.) generator.**

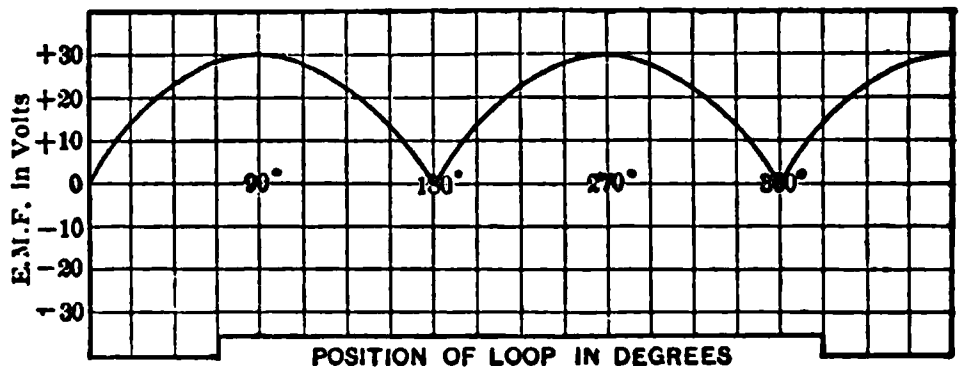

Fig. 372. Curve showing pulsating e.m.f. delivered by loop fitted with commutator.

341. Generators of steady currents. The e.m.f. produced by rotating a single loop in a magnetic field can be raised by using many turns of wire and by rotating the coil very fast. Nevertheless the current will be pulsating, and this is unsatisfactory for many purposes. To get a machine to

deliver a *steady* current, a Frenchman, named Gramme, invented in 1870 the so-called **Gramme-ring** form of armature.

The Gramme-ring armature is now very seldom used, but it is worth studying carefully because the fundamental principles of its action can be understood from very simple diagrams; whereas most armatures of the common or drum type, although based on exactly the same principles, cannot be represented by simple diagrams.

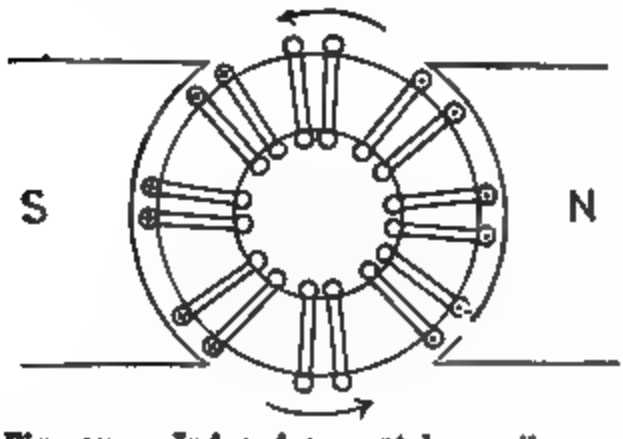

Fig. 373. Magnetic field in a Gramme ring.

A rotating soft-iron ring or hollow cylinder is mounted between the poles of an electromagnet, as in figure 373. The ring serves to carry the flux across from one pole to the other. There are scarcely any lines of force in the space inside the ring. A continuous coil of insulated copper wire is wound on the ring, threading through the hole at every turn. When the ring rotates, as in figure 374, the wires on the *outside* are cutting lines of force, but those inside are not. Furthermore, according to the right-hand rule, the outside wires on the right-hand side are moving in such a direction that the induced current tends to flow toward us. The wires lying on the other side of the ring are moving so as to induce a current away from us. If there were no outside connections, these two opposing e.m.f.'s would just balance, and no current would flow. This would be like arranging a number of cells in series with an equal number turned so that they are opposed to the

Fig. 374. Induced current in a coil on a Gramme ring rotating in a magnetic field.

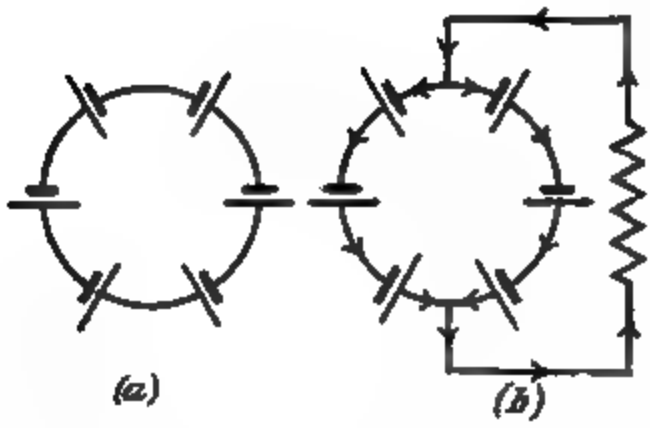

Fig. 375. Opposing batteries (a) without, and (b) with an external circuit.

first group (Fig. 375 (*a*)); obviously no current would flow.

But if we imagine the copper wires on the outer surface of the ring to be scraped bare, and if two metal or carbon blocks or **brushes** at the top and bottom rub on the wires as they pass, a current could be led out of the armature at one brush, and, after passing through an external resistance, such as a lamp, could be led back to the armature again at the other brush. In this case the armature circuit is *double*, consisting of its two halves in parallel. It is like adding an external circuit to the arrangement of cells described above. This battery analogue for a Gramme-ring armature is shown in figure 375 (*b*).

In the Gramme-ring arrangement there are at every instant the same number of active conductors in each half of the armature circuit, and so the current delivered by the armature is not only *direct* but also *steady*.

In practice, however, it would be difficult to make a good contact directly with the wires of the armature, because the wires must be carefully insulated from each other and from the iron core; and so the various turns of wire, or groups of turns, have branch wires which lead off to the commutator segments, as in figure 376.

The **commutator** consists of copper bars, or segments, which are arranged around the shaft

Fig. 376. Ring armature with commutator.

and insulated from each other by thin plates of mica (Fig. 377). To get a satisfactorily steady current there should be many segments in a commutator, so that the brushes may always be connected to the armature circuit in the most favorable way.

342. Drum armature. Since very little flux passes across the air space in the center of a Gramme-ring armature, the wires on the inner surface of the ring do not cut lines of magnetic force and are useless, except to connect the adjoining wires on the outer surface. Furthermore, it is very inconvenient to wind the wire on an armature of the ring form. For these reasons most armatures are now of a **drum** type. In this form the core is made with slots along the circumference, in which the wires lie (Fig. 378). Since the active wires in one slot are connected across the end to active wires in another slot, there are no idle wires inside the core.

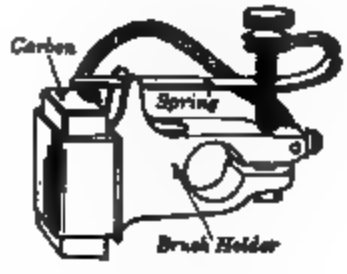

Fig. 377. Commutator and brush with its holder.

343. Multipolar generators. The machines which have been described are called **bipolar** machines. For commercial purposes, especially in large machines, it is common practice to use four, six, eight, or even more poles. Such machines are called **multipolar.** By increasing the number of poles, we can get the commercial voltages (110, 220, or 500 volts) at much slower speeds than would be necessary in a bipolar machine. We have already seen that the voltage de-

Fig. 378. Slotted armature core, drum type. Partly wound.

pends on the rate at which the wires of the armature cut the lines of magnetic force. But in a four-pole machine (Fig. 379) each wire on the armature cuts a complete set of lines of force four times in each revolution instead of twice as in a two-pole

Fig. 379. Four-pole generator and its diagrammatic cross section.

machine. For this reason the speed of a four-pole machine is one half the speed required in a two-pole machine for the same voltage. Furthermore, the multipolar machine is more economical to build because it requires less iron to carry the magnetic flux. It will be observed from the diagram (Fig. 379) that every other brush is positive and is connected to the positive terminal of the machine.

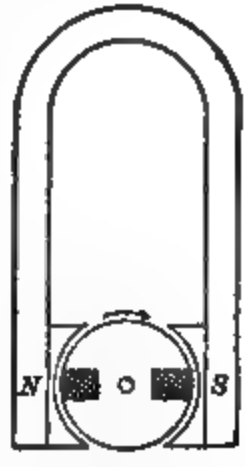

Fig. 380. Magneto with permanent magnets and slotted armature core.

344. Excitation of the field of generators. In the magneto (Fig. 380) the magnetic field is supplied by permanent steel magnets. In most other generators the magnetic field is furnished by powerful electromagnets. Sometimes the current needed

to excite these magnets is supplied by some outside source, such as a storage battery; but generally the machine itself furnishes the exciting current. There are three types of generators, differing in the method of exciting the field coils: (1) *series-wound*, in which the whole current generated passes through the field coils on its way to the external circuit; (2) *shunt-wound*, in which the field is excited by diverting a small part of the main current, the field coils and the external circuit being in parallel or in shunt; and (3) *compound-wound*, with both series and shunt coils.

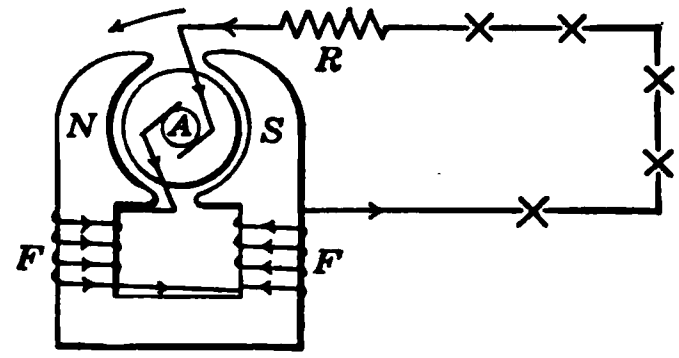

Fig. 381. Connections of a series arc-light machine.

In the **series** generator (Fig. 381) the field coils are wound with a few turns of large wire. When the current in the external circuit increases, the field is more highly magnetized, and so a higher voltage is available to supply the current. This machine is used to furnish current for arc lamps which operate on a constant current.

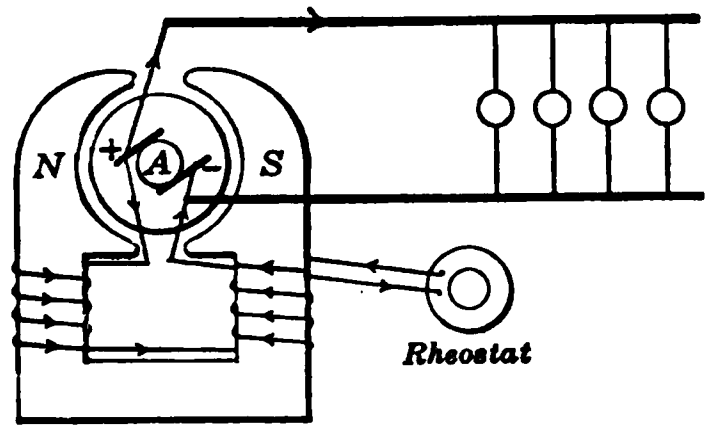

Fig. 382. Connections for a shunt-wound generator.

When the field is **shunt-wound** (Fig. 382), the coils have **many turns of small wire**; for in this case it is desirable to divert as little current as possible from the main circuit, and so the resistance of the field coils should be high. Such machines are run at constant speed. When more load is thrown on the machine, that is, when more lamps are turned on, so that more current is needed, the terminal voltage drops a little. This decreases the current in the field coils and still further reduces the terminal voltage. A shunt machine, therefore, cannot be used when very constant voltage is desired.

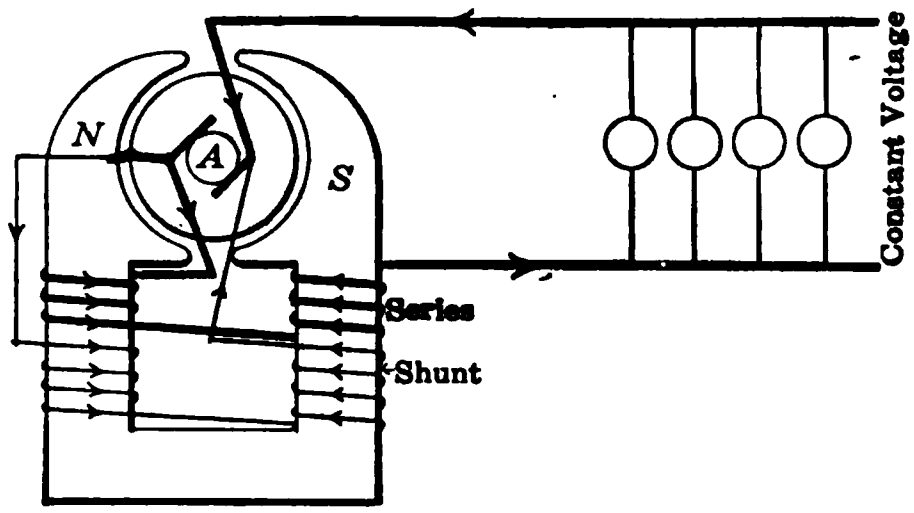

Fig. 383. Connections for compound-wound d-c. generator.

This drop in the terminal voltage of shunt generators under heavy loads can be overcome by the

use of the **compound-wound** generator (Fig. 383), which is the one most commonly used. Here the voltage is kept constant by adding a series coil of a few turns; this tends to raise the voltage when the current increases, just as in a series generator. If the coils are carefully adjusted, the voltage remains practically constant at all loads.

Fig. 384. Direct-current generator connected directly to a steam engine.

345. Source of energy in the generator. It is important to remember that the electric generator *cannot* of itself *make electricity*, but can only *transform* mechanical energy into electrical energy. For example, if we want to light a house with electricity, it is not enough for us to buy a generator; we must also get a steam engine (Fig. 384), a gas engine, or a water wheel with which to *drive* the generator. We have already seen that the induced current is always in such a direction as to oppose the motion of the wire. Consequently, the greater the current in the generator, the greater the power needed to turn it. Large generators, such as are used in power stations to furnish electricity for street railways and city lighting

systems, sometimes require steam engines of 20,000 to 40,000 horse power capacity.

QUESTIONS

1. If a person stands facing in the direction of a magnetic flux, and thrusts downward a wire which he holds in his two hands, in which direction is the induced e.m.f.?

2. What are the three factors which determine the voltage of a generator? How does each affect the voltage?

3. How many revolutions per minute (r.p.m.) would a single-coil bipolar dynamo have to make in order that the current might have 60 cycles per second?

4. How many revolutions per minute would an eight-pole generator have to make in order to generate a 60-cycle alternating current?

5. Why are carbon blocks generally used instead of copper brushes?

ELECTRIC MOTOR

346. The generator as a motor. We have already seen that a generator, when driven by a steam engine, gas engine, or water wheel, may *generate* electricity. Now we shall see how this electric current can be supplied to a second machine, exactly like a generator but called a **motor**, which may be used to drive an electric car, a printing press, a sewing machine, or any other machine requiring mechanical energy. In short, the generator is a *reversible* machine, and sometimes in shops, and often on self-starting automobiles, the same machine is driven as a generator part of the time, and used as a motor to drive another machine the rest of the time.

Structurally, the motor, like the generator, consists of an electromagnet, an armature, and a commutator with its brushes. To understand how these act in the motor, however, we must get a clear idea of the behavior of a wire carrying an electric current in a magnetic field.

347. Side push of a magnetic field on a wire carrying a current. We stretch a flexible conductor loosely between the two binding posts *A* and *B*, so that a section of the conductor lies between the poles of

an electromagnet, as shown in figure 385. Let the exciting current be so connected to the electromagnet that the poles are *N* and *S* as shown. Then, if a strong current from a storage battery is sent through the conductor from *A* to *B* by closing the key *K*, it will be seen that

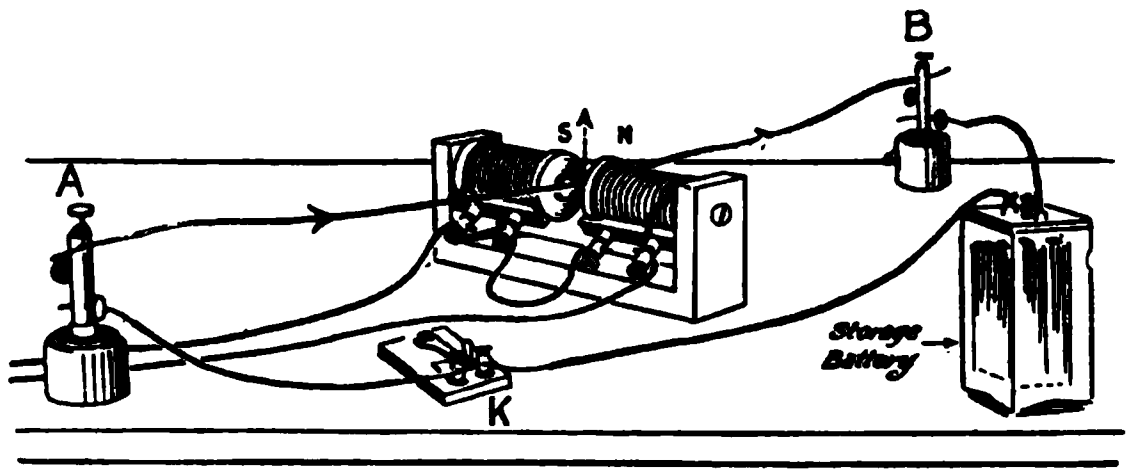

Fig. 385. Side push on wire carrying a current.

the wire between the poles of the magnet is instantly thrown *upward*. If the current is sent from *B* to *A*, the motion of the conductor is reversed, and it is thrown *downward*.

The magnetic field between the poles of a strong magnet is practically uniform and is represented by parallel lines of force shown in figure 386.

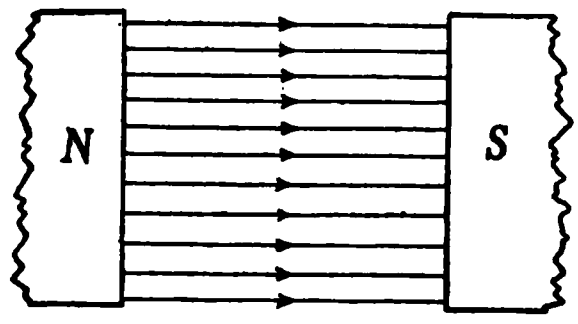

Fig. 386. Uniform magnetic field of magnet alone.

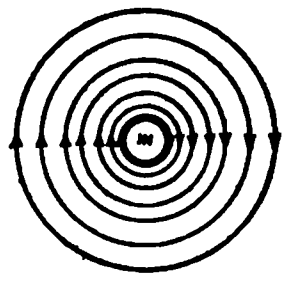

Fig. 387. Field of current alone.

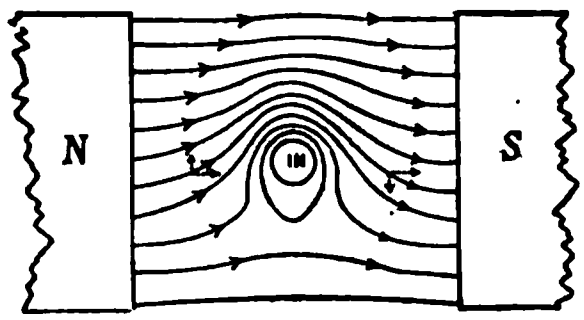

Fig. 388. Lines of force about a wire carrying current in a magnetic field.

It will help us to understand this side push exerted on a current-carrying wire in a magnetic field if we recall that every current generates a magnetic field of its own, the lines of which are concentric circles. Figure 387 shows a wire carrying a current *in*, that is, at right angles to the paper and away from us. The lines of force are going around the wire in clockwise direction.

If we put the wire, with its circular field, in the uniform field between the *N* and *S* poles of the magnet, the lines of force are very much more crowded above the wire (Fig. 388) than below. But we have seen in section 252 that we can think of magnetic lines of force as acting like stretched rubber bands which would, in this case, push the wire down. If the current in the wire is reversed, the crowding of the lines of force comes below the wire, and it is pushed up.

348. Motor rule of three fingers. The rule for remembering which way this side push on a wire in a magnetic field will move the wire is precisely the same as that for the generator, except that the **left hand** instead of the right is used.

349. The action of a motor. In motors, as in generators, the drum type of armature (see section 342) is almost exclusively used. It will be remembered that in this type the active wires lie in slots along the outside of the drum, as in figure 389; and the wiring connections across the ends of the armature are such that when the current is coming *out* on one side — say the right — it will be going *in* on the other side — the left. Just how these wiring connections are made is not important for the present purpose; and indeed there are many different ways in which they can be arranged. In any case, from what has just been said, it will be clear that the wires (⊙) on the right side of the armature will be pushed *upward*, and those (⊗) on the left side of the armature will be pushed *downward* by the magnetic field. In other words, there will be a **torque** tending to rotate the armature counter-clockwise. The amount of this torque depends on the number and length of the active wires on the armature, on the current in the armature, and on the strength of the magnetic field.

Fig. 389. Connections of a drum-wound motor.

Another way of looking at this action is to notice that the

effect of these armature currents is such as to make the armature core a magnet, with its north pole at the bottom and its south pole at the top. The attractions and repulsions between these poles and those of the field magnet cause the armature to rotate as indicated by the arrows.

The function of the commutator and brushes is, as in the generator, to reverse the current in certain coils while the armature rotates, in order to keep the current circulating, as shown in figure 389.

350. Forms of motors. Direct-current generators and motors are often of identical construction. Thus we have **series** motors, such as are used on street cars and automobiles, and **shunt** motors, such as are used to drive machinery in shops. So also we have **bipolar** and **multipolar** motors. When it is desirable that a motor shall run at a slow speed, it is built with a large number of poles.

Between the main poles of most modern d-c. generators and motors are smaller poles, called **interpoles** or **commutating poles** (Fig. 390), which are supplied with series field coils so that their strength depends upon the armature current. They are not there to generate power in the armature, but are merely to keep the brushes from sparking on heavy loads or high speeds. For the explanation of their action, the student is referred to special books on electrical machinery.

Fig. 390. Direct-current four-pole motor with four interpoles.

351. Back e.m.f. in motor. Suppose we connect an incandescent lamp in series with a small motor. If we hold the armature stationary, and throw on the current from a service line or storage battery, the lamp will glow with full brilliancy; but when the armature is running, the lamp grows dim.

This shows that *a motor uses less current when running than when the armature is held fast.* The electromotive force of the line or battery and the resistance of the circuit are not changed by running the motor. Therefore, the current must be diminished by the development of a **back electromotive force**, which acts against the driving e.m.f.

Since a motor has a series of armature wires cutting magnetic lines of force, it is bound to generate an e.m.f. in these wires. That is, every motor is at the same time a generator. The direction of this induced e.m.f. will always be opposite to that driving the current through the motor.

Just as in the generator, when the armature revolves faster, the back e.m.f. is greater, and the difference between the impressed e.m.f. and the back e.m.f. is therefore smaller. This *difference* is what drives the current through the resistance of the armature. So a motor will draw more current when running slowly than when running fast, and much more when starting than when up to speed.

FOR EXAMPLE, suppose the impressed, or line, voltage on a motor is 110 volts, and the back e.m.f. is 105 volts. Then the *net* voltage which will force current through the armature is 110 − 105, or 5 volts. If the armature resistance is 0.5 ohms, the armature current is 5.0/0.5, or 10 amperes. But if the whole voltage (110 volts) were thrown on the armature while at rest, the current would be 110/0.5, or 220 amperes.

352. Starting a motor. When a motor starts from rest, there is, of course, no back e.m.f. at first, and if the motor is thrown directly on the line, there will be such an excessive current as to "burn out" the armature. To prevent this first rush of current, a *starting resistance* is put into the

circuit at first, and cut out step by step as the machine speeds up. The device for doing this is shown in figure 391.

Applications of the Motor

363. Shunt motors. The transmission of power through shops and factories by means of shafting, cables, and belts is dangerous, noisy, and uneconomical. In a modern system, electric power is generated in a central power house, is transmitted to various parts of the plant, and is used in electric motors to drive either individual machines or groups of machines. When electrical transmission is used, the danger and inconvenience of belts and shafting are avoided, the machines can be set in any position, and their speed can be easily controlled by field rheostats. In shops and factories thus equipped, shunt motors are commonly used; for constant speed motors are required, and the speed of a shunt motor under no load, or a light load, is nearly the same as at full load.

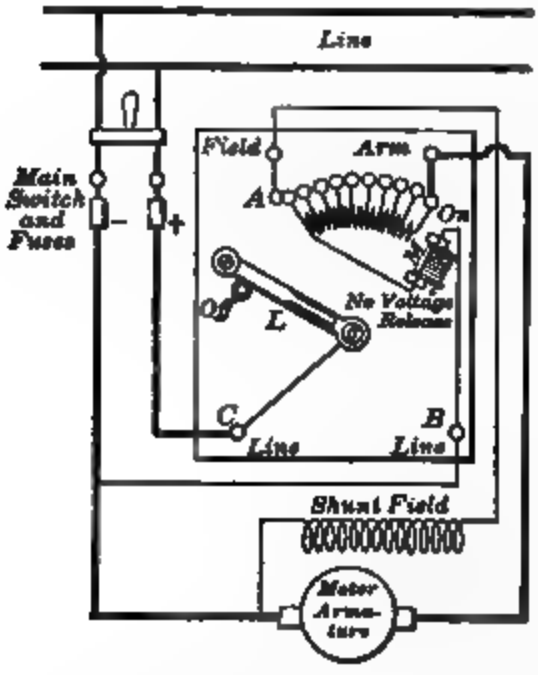

Fig. 391. Diagram of starting box connected with shunt-wound motor.

Electric motors have also become a great convenience and comfort in the household. Thus, we have little shunt motors to drive sewing machines (Fig. 392) and to drive the compressors of the small refrigerating plants for iceless refrigerators.

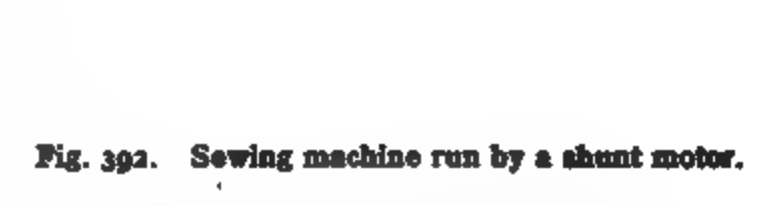

Fig. 392. Sewing machine run by a shunt motor.

354. Series motors. On cranes and on electric automobiles and cars, **series** motors are used, because this type of motor has **a large starting torque.** The torque in a series motor is proportional to the *square* of the current, while in a shunt motor it is *directly* proportional to the current. The fact that the torque in a series motor is largest when the speed is slowest (because there is little back e.m.f.) makes it just the kind of motor for crane or vehicle work. When the load on a series motor drops to zero, the motor may "race"; that is, go faster and faster until the armature flies to pieces. For this reason, series motors are connected, either directly (on the same shaft) or by cogwheels, to the machines which are to be driven, so that they can never escape their load.

Fig. 393. Street-car motor with top of case lifted.

Figure 393 shows a street-car motor with its case lifted to display the inside arrangement. The field consists of *four* short poles projecting from the case, which serves both to protect the motor and as a path for magnetic flux. The armature revolves so rapidly that its speed has to be reduced by a pair of cogwheels, the larger of which is on the axle of the driving wheels, and is not shown in the picture. These make the speed of the axle about one fourth that of the motor.

Street cars are usually operated on a direct-current system. A large multipolar, compound-wound generator at the power station maintains about 550 volts between the trolley or third rail and the track. A "feeder," or cable of low resistance, is run parallel to the trolley wire and connected to it at intervals, to avoid a large voltage drop in the line when a number of cars are taking current at a distance from the power plant.

The current (Fig. 394) passes down the trolley pole into the **controller.** This is an ingenious arrangement of switches by which the motorman can start his car with both motors in series and with the starting resistance all in; then by moving a lever he

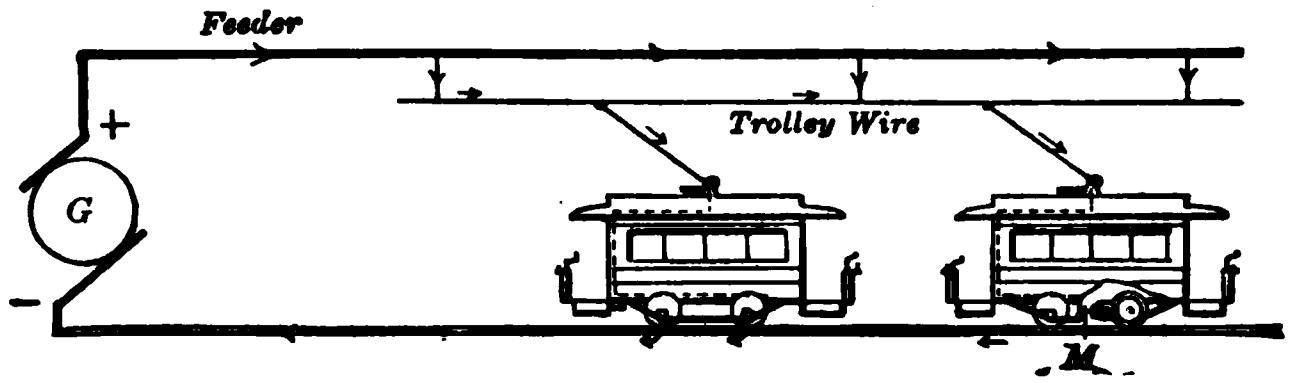

Fig. 394. Diagram showing the fundamental features of the electric railway.

gradually cuts out the starting resistance and finally throws both the motors in parallel, as shown in figure 395. Thus, when starting, each motor receives less than half the line voltage, and when running at full power, gets full voltage. The current leaves the motors by the wheels, and goes back to the power station through the rails.

355. Efficiency of the electric motor. One reason for the extensive use of electric motors is their great efficiency, sometimes as high as 80% or 90%. The **efficiency** of a motor, just as of any machine, means the *ratio of output to input.* We can easily measure the number of amperes and the number of volts supplied to the motor and thus compute the **watts put in.**

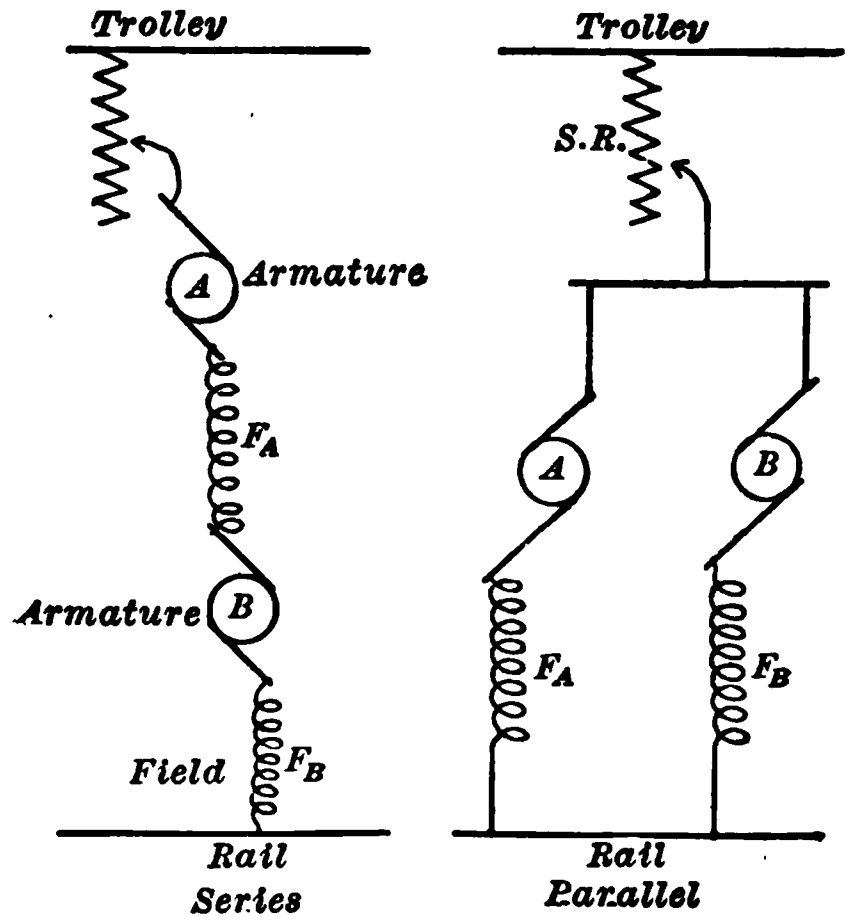

Fig. 395. Diagram of series-parallel control of electric cars.

To get the **output** of mechanical work, engineers usually make a "brake test." One simple form of brake consists of

a belt or cord attached to two spring balances and passing under a pulley on the motor shaft, as shown in figure 396.

If the pulley rotates as indicated, it is evident that one spring balance will have to exert more force than the other because of the friction of the pulley on the cord. *The amount of friction is equal to the difference between the readings of the two balances, and it is exerted each minute through a distance equal to the circumference of the pulley times the revolutions per minute.* The **work done** in one minute is equal to the friction times the distance per minute.

Fig. 396. **Measuring the output of a motor by means of a brake.**

Finally, if we express the output and input in some common unit of power and divide, we have the efficiency. It will be helpful to know that

1 watt = 44.3 foot pounds per minute,
= 6.12 kilogram meters per minute.

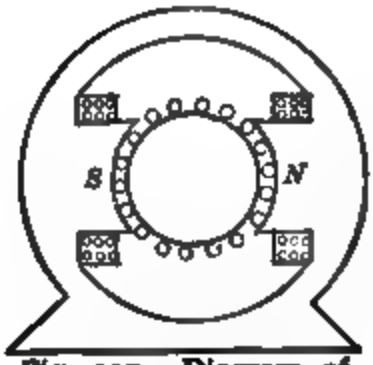

Fig. 397. **Diagram of a bipolar motor.**

Questions and Problems

1. Figure 397 represents a bipolar motor with the armature revolving counter-clockwise. Copy it and indicate by dots and crosses * in the circles the direction of the various currents in both the armature and field coils.

*A cross in a circle represents the feathers of an arrow piercing the paper, and means a current going *in*. A dot in a circle means a current coming *out*.

2. What is the armature resistance of a motor in which the armature current is 4 amperes, the impressed e.m.f. is 115 volts, and the back e.m.f. is 112 volts?

3. Find the back e.m.f. in a motor in which the armature resistance is 0.3 ohms, the current is 15 amperes, and the impressed voltage is 110 volts.

4. How much current will be drawn by a motor whose efficiency is 90%, when it is developing 5 horse power and is connected to the 110-volt service?

5. When a certain motor was tested by the brake test, it took 67 amperes at 113 volts and developed 8.5 horse power. Calculate its efficiency.

6. What advantages are there in driving the propellers of an ocean liner by electric motors? What advantages in a battleship?

7. Why are electric cars not more generally operated on storage cells instead of by an overhead or third-rail system of transmission?

8. What methods are used to make the track of a street-car system a better conductor?

9. Does it make any difference which end of the field coils of a shunt-wound generator is connected with the positive brush? If you have an experimental generator, try it.

10. The speed of a shunt-wound motor can be controlled by putting an auxiliary resistance, called a field-rheostat, in series with its field coils, so as to decrease the current through them. Will this increase or decrease its speed? Why? If you have an experimental motor, try it.

Practical Exercise

Testing a starter-generator. Get a secondhand starter (such as a Dodge or a Ford) from an automobile repair shop. Take it apart and examine the field coils, the armature, commutator, and brushes. Reassemble the machine and measure its efficiency as a starting motor. Find out how the *third-brush* operates to regulate the current when charging the storage battery. (See *Hobbs, Elliott, and Consoliver's* The Gasoline Automobile — McGraw-Hill Book Co.)

Other Applications of Induced Currents

356. Currents induced by currents. Since an electromagnet can be made more powerful than a steel magnet, we

should expect greater induced currents when we move an electromagnet near a coil.

We shall connect the secondary coil S in figure 398 to a galvanometer, and the primary coil P to a battery. When we move the current-carrying primary coil P either into or out of the other coil S, a current is induced, just as when we move a magnet in and out of a coil. The induced current is, however, much greater. We find also that a stronger current in the coil P increases the strength of the magnetic field, and so of the induced current.

We may also increase the induced current by inserting an iron core inside the primary coil. This greatly strengthens the magnetic field and so increases the number of lines of force about the coil.

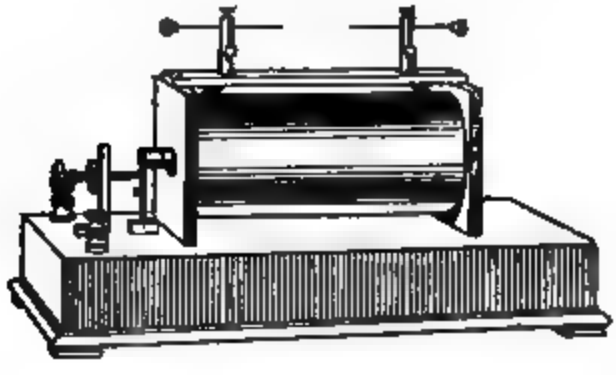

Fig. 398. A moving electromagnet generates a current.

If we put the primary coil with its iron core inside the secondary coil, we can generate an induced current by opening and closing a switch in the primary circuit. When the switch is opened and closed, the deflections are in opposite directions.

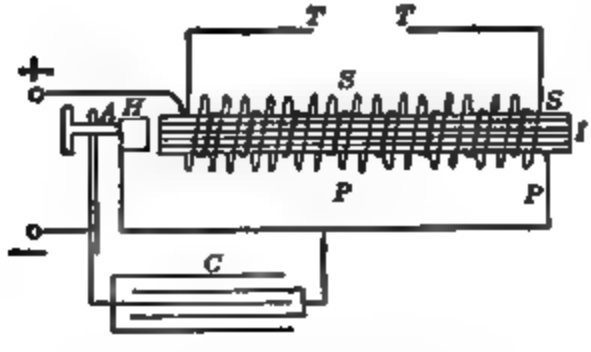

Fig. 399. Induction coil and diagram of connections.

In general we see that an *induced current is set up in a coil whenever there is a change in the number of lines of magnetic force passing through the coil.*

357. Induction coil. In the induction coil (Fig. 399) the core I is made of soft-iron wires; the primary coil P consists of a few turns of large copper wire, and the secondary coil S, which is

carefully insulated from the primary, contains many turns of very small silk-covered copper wire. To make and break the primary current very rapidly, an interrupter *H* is commonly made to operate on the end of the coil. This automatic make-and-break works exactly like the vibrating electric bell described in section 301. When the primary circuit in such a coil is broken, the current tends to keep on as if it had inertia, and may jump the switch gap at *A* even after it has opened slightly. This slows up the " break " and weakens the induced e.m.f. So a condenser *C* is connected across the gap. It is usually made of sheets of tin foil, insulated by paraffin paper, arranged as shown in figure 399. This furnishes a storage place into which the current can surge when broken, and diminishes the sparking at the interrupter. Even with a condenser there is some sparking, and so the contact points have to be tipped with silver or tungsten and frequently cleaned.

Coils are generally rated according to the distance between the terminals of the secondary across which a spark will jump. When the coil is in operation, sparks jump across this gap in rapid succession, provided the terminals are close enough together. This type of coil is sometimes called a **Ruhmkorff coil.**

358. Uses of induction coils. The most important practical application of the induction coil is undoubtedly for **ignition in gas engines.** To make a spark jump between the terminals of the **spark plug** (Fig. 400), several thousand volts are required.

Fig. 400. Cross section of a gas-engine spark plug.

There are a number of systems for producing this high-voltage current on automobiles. In the Ford car a magneto with rotating horseshoe magnets induces an alternating current in a series of coils which are attached to the flywheel case. Then this low-tension current is raised to a high voltage by four induction coils and applied directly to the spark plugs. In the wiring diagram shown

in figure 401, it will be seen that the primary circuit includes a timer, which is a rotating switch for closing the circuit for each of the four cylinders at just the right time. It will also be seen that the return high-voltage circuit is through the motor frame itself.

On the Liberty aircraft engine and on many automobile and marine engines, the direct current is supplied by a generator and a storage

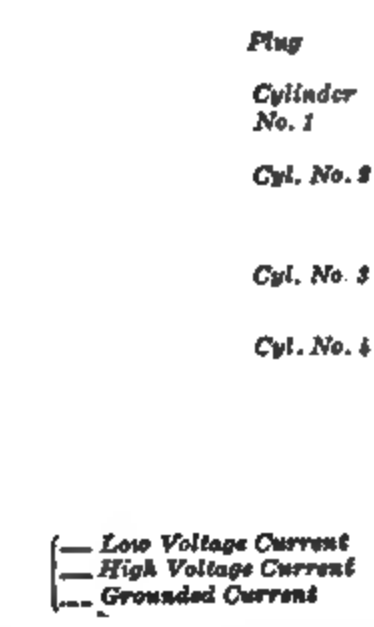

Fig. 401. Diagram of the ignition system of the Ford automobile engine. A coil for each cylinder.

battery with a voltage-regulating device. The low-voltage current is transformed to a high-voltage current by means of an induction coil. In this system there are one induction coil, one interrupter, and a distributor which transmits the high-voltage current to the various spark plugs in turn. The principle of this system is shown in figure 402.

In still another system a **high-tension magneto** is used, which comprises within itself the means for generating and intensifying the current, so that all that is needed to complete the ignition system is a set of spark plugs and some connecting wires.

Induction coils are also used in connection with storage batteries in portable apparatus for **exciting X-ray tubes** and for setting up electric waves for **radio telegraphy**. These will be described in Chapter XXIII.

359. Self-induction or inductance. If a coil of wire with many turns and with a soft-iron core is connected with a bat-

tery (Fig. 403), it can be shown that when the switch is closed the current does not instantly attain its full value as determined by Ohm's law. The reason for this growth of the current

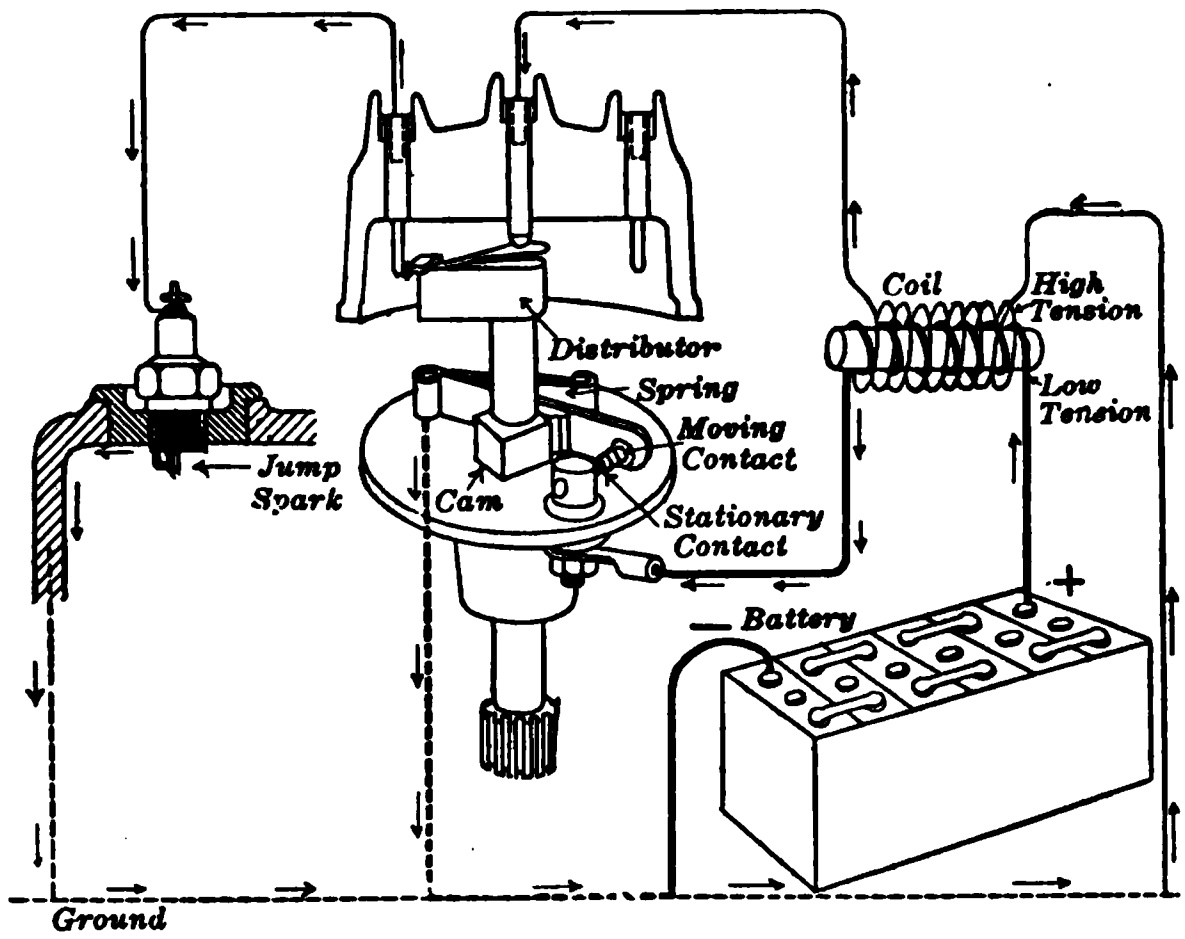

Fig. 402. Diagram of automobile ignition system using battery, spark coil, and high-tension distributor.

(which of course takes a very short time) is the fact that the current is building up a magnetic field, and that as this

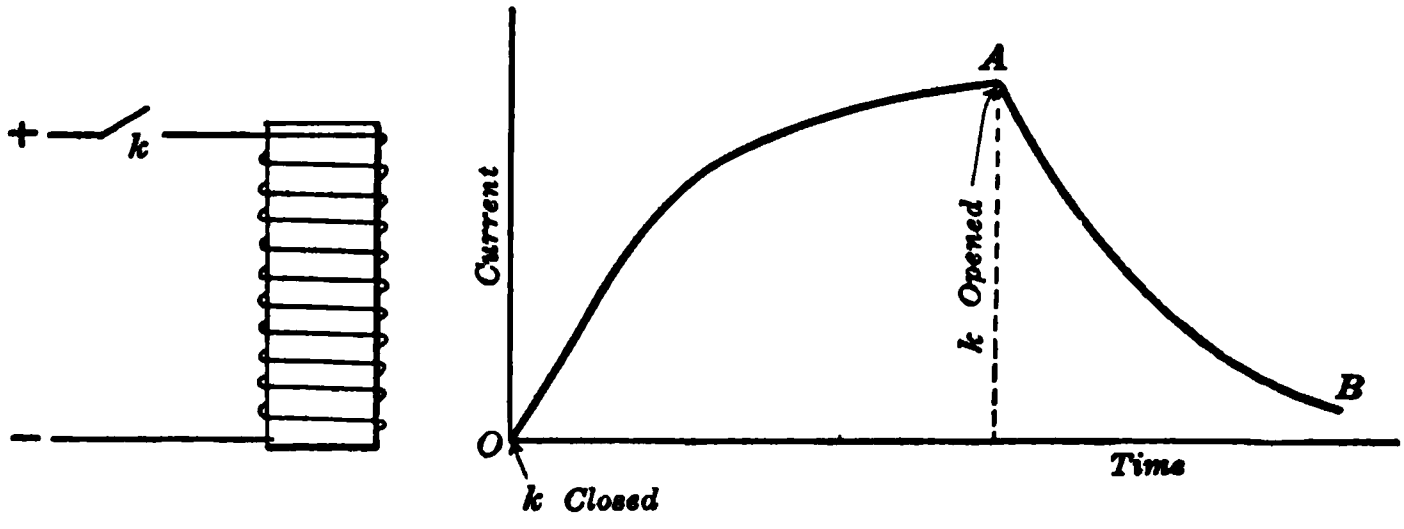

Fig. 403. Growth and decay of current in an inductive circuit.

field grows, its lines of force cut the turns of the coil and *induce in them a voltage, which opposes the growth of the current.*

When the switch is opened, the original current does *not* drop *instantly* to zero, but tends to arc across the switch gap and keep on flowing. As the current's own magnetic field dies away, the lines of force again cut the turns of the coil; but this time, in such a direction that the *self-induced voltage upholds the current.*

That property of an electric circuit whereby it opposes a change in the current flowing is called the ***self-induction*** *or the* ***inductance*** *of the circuit.* This property of an electric circuit is sometimes called its electromagnetic **inertia**, because it is quite like the property of inertia, which we find in all machines.

360. Applications of self-induction. The principle of self-induction is made use of in **make-and-break ignition.** A *single* coil is used, consisting of many turns of wire wound on a soft-iron core. When such a coil is employed to furnish a spark in the cylinder of a gas engine, the circuit is as shown in figure 404. The terminals are two points inside the cylinder of the engine, one stationary (A) and the other moving (S). When A and S separate, the self-induction of the coil causes enough induced e.m.f. to make a spark jump across the gap between them.

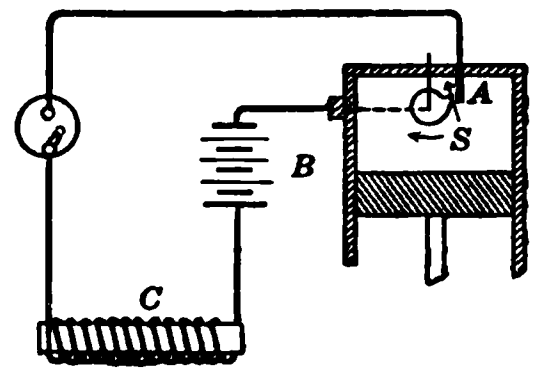

Fig. 404. Make-and-break spark coil used for gas-engine ignition.

This is the kind of coil which is used to light gas burners in houses by means of a battery current. If the circuit of a large electromagnet, such as the field of a dynamo, is broken while one is touching the conductors on either side of the gap, the current due to self-induction sometimes gives a severe shock.

PRACTICAL EXERCISE

Connecting an automobile ignition system. Get the essential parts of the Ford ignition system, such as the spark plugs, the timer, and the spark coils. Connect them as in figure 401 and mount the spark plugs so as to show the successive sparks as the timer rotates. Dry cells may be used in place of the magneto.

The Telephone

361. Telephone receiver. In 1876 Alexander Graham Bell astonished the world by showing that the sound of a human voice could be transmitted by electricity. The essential part of his apparatus was what we still use and know as the **Bell receiver.** The hard-rubber case contains a steel U-shaped magnet, which has around each pole a coil of many turns of very fine wire (Fig. 405). A disk of thin sheet iron is so supported that its center does not quite touch the ends of the magnet. A hard-rubber cap or earpiece with a hole in the center holds the disk in place.

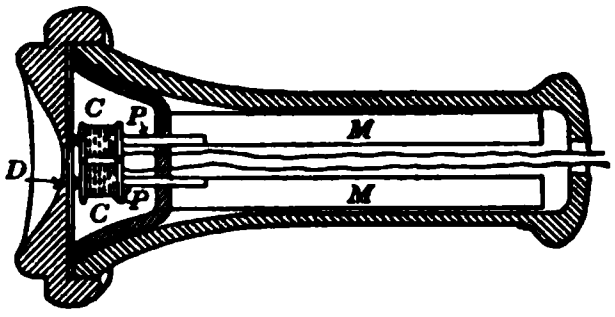

Fig. 405. Parts of a bipolar telephone receiver.

To show the operation of the telephone receiver, we may connect a large receiver, in series with a lamp, to the a-c. mains or to a magneto which furnishes an alternating current. We immediately hear a loud hum. If we hold the receiver upright and stand a pencil on the diaphragm, it dances up and down. The alternating current, sent through the coil, alternately strengthens and opposes the magnet, which attracts the disk alternately more and then less, thus causing it to vibrate. This sets the air to vibrating and produces sound.

362. The microphone. To show how the right sort of currents can be produced to make a telephone receiver speak words instead of merely humming, we shall set up an old-fashioned instrument called a microphone.

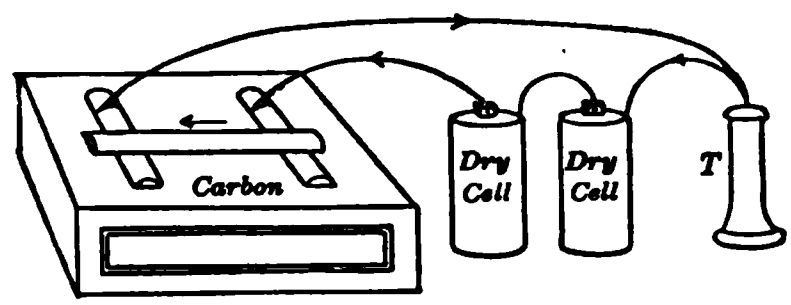

Fig. 406. Simple form of microphone.

A simple microphone can be made out of three lead pencils, or three pieces of electric-light carbon (Fig. 406). If such a microphone is connected in series with a battery and telephone receiver, and a watch is laid on its baseboard, the ticks can be heard in the telephone even if it is some distance away. The little jars which the watch gives the baseboard shake the car-

bons so that the resistance at their points of contact varies and thus changes the current. The changing current then pulls the telephone diaphragm back and forth, and sets the surrounding air in motion.

363. The telephone transmitter. The modern telephone transmitter is simply a carefully designed microphone. It contains a little box *C* (Fig. 407) which is filled with granules of hard carbon. The front and the back of the box are polished plates of carbon, and the sides of the box are insulators. The front carbon is attached to the center of the diaphragm *D*, and moves in and out a little when the diaphragm vibrates. The other plate is fastened rigidly to the solid back of the case. A current from a battery flows to the front plate, then back through the granules to the other plate, and out along the telephone line to a receiver. When the diaphragm moves back a little, it compresses the granules, their resistance decreases, and the current gets stronger and pulls the diaphragm of the receiver back also. When the transmitter diaphragm moves out, the current decreases and the receiver diaphragm moves out also. So all the motions of the transmitter diaphragm are reproduced by the receiver diaphragm. If one speaks into the transmitter, causing its diaphragm to move in a corresponding way, the receiver diaphragm moves in the same way and produces the same kind of waves in the surrounding air.

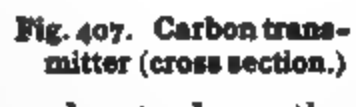

Fig. 407. Carbon transmitter (cross section.)

364. Central batteries and local batteries. The system we have just described is the one in use in all large cities. The battery is a large storage battery (or a generator) at the central station, and is used on all the lines that happen to be busy at any instant.

In many country exchanges and on isolated lines another system, called the local-battery system, is used because it is cheaper to install and maintain. Even in cities something equivalent to this system is used on long-distance lines.

In this system (Fig. 408) each subscriber's telephone set contains a few dry cells which are connected in series with his transmitter, as already described. But the varying current produced, instead of being sent directly out on the line, goes to the primary of a little induction coil and back to the battery. The secondary of the induction coil meanwhile sends out into the line an induced current that varies exactly like the primary current, but is at much higher voltage. This makes the "line losses" much smaller, and so more energy gets through to the receiver than if the original current had been transmitted directly. This system is really better, electrically, than the central-battery system. It is not used in large cities, chiefly because of the trouble involved in keeping so many local batteries in proper working condition.

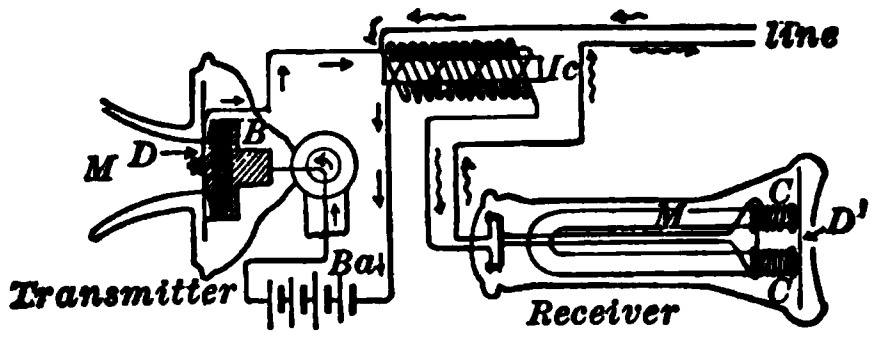

Fig. 408. Diagram of local-battery telephone system.

Practical Exercise

Setting up a two-party telephone line. For full directions and diagrams, see *Good's* Laboratory Projects in Physics (Macmillan Co.).

SUMMARY OF PRINCIPLES IN CHAPTER XVII

Induced current exists *only* when the number of lines of force through the circuit is *changing*.

Induced current has such a direction as to *oppose* the *motion* which causes it. Lenz's law.

When a wire cuts lines of force, an induced e.m.f. is set up.

To get direction of induced current, use *right* hand.

Thumb shows the motion.

Forefinger shows the flux.

Center finger shows direction of current.

Magnitude of e.m.f. varies as speed × flux × turns.

Commercial generator with
slip rings gives alternating current,
commutator gives direct current.

Generator does not _make_ energy; it _transforms_ mechanical into electrical energy.

Motor transforms electrical energy into mechanical energy.

A wire carrying a current, when set at right angles to a magnetic field, is pushed sidewise by the field.
To get direction of motion, use _left_ hand.

Every motor, when running, is acting at the same time as a generator. The e.m.f. of this generator action opposes the current driving the motor, and is the _back_ e.m.f.

Net e.m.f., which drives current through armature, equals impressed e.m.f. minus back e.m.f.

Ohm's law applies to a motor armature _only_ if _net_ e.m.f. is used.

Self-induction, or inductance, means that the magnetic field around a coil tends _to oppose any change_ in the current.

QUESTIONS

1. How should a coil of wire be rotated in the earth's magnetic field to get the maximum induced current?

2. How might a coil of wire be rotated in the earth's magnetic field so as to get no induced current?

3. Why are one-coil armatures not used commercially?

4. Why must the power applied to a generator armature be increased if the current generated is increased and the voltage is kept constant?

5. What becomes of the energy lost in a generator?

6. Why is the price of electricity dependent on the price of coal or the availability of water power?

7. Of what use is residual magnetism when a generator is started?

8. A belt-driven, shunt-wound generator is used to charge a storage battery. The belt breaks, but the machine keeps on running. Explain.

9. Why does an electric truck take more current going uphill than on the level?

10. Explain how the law of conservation of energy applies to the input and output of a motor.

11. What is the difference in the construction and use of a field rheostat and a starting rheostat?

12. Find out how the motor-generator used for starting an automobile and for charging a storage battery maintains a constant voltage at varying speeds.

13. What are the advantages of the two-unit system (that is, separate motor and generator) for starting an automobile and charging its storage battery?

14. What are the essential differences between the current in the primary winding of the induction coil and that in the secondary winding?

15. What is the function of the magneto in a local-battery telephone system?

16. Why is it dangerous to touch the terminals of the secondary of a large induction coil?

17. Why is the induced e.m.f. in the secondary of an induction coil so much greater at the break of the primary than at the make?

18. Why is it that the self-induction of a circuit is not apparent as long as the current is steady?

19. An electrical impulse passes over the telephone wires from Boston to San Francisco in about one fifteenth of a second. How long would it take sound to travel that distance through the air?

20. In the very first telephones, two telephone receivers were connected together. Could you use telephone transmitters in the same way? Explain.

PRACTICAL EXERCISE

Thermoelectric currents. Twist together the ends of a small copper wire and a small iron wire and connect the other ends to a millivoltmeter. Apply the heat of a burning match to the twisted ends of the wires. The voltmeter shows that an electric current is generated. When the twisted wires are cooled with ice, the current is in the opposite direction.

Find out how a thermoelectric pyrometer is made and how it is used in measuring the temperature of furnaces.

CHAPTER XVIII

ALTERNATING CURRENTS

Why alternating currents are used — the transformer — long-distance transmission — eddy currents — impedance — a-c. power — capacity — alternators — polyphase circuits — a-c. motors — rotating field — squirrel-cage rotor — watt-hour meters — rectifiers.

365. Why alternating currents are used. For heating and lighting purposes an alternating current is just as satisfactory as a direct current. For plating and refining, an alternating current cannot be used, because a unidirectional current is necessary to make a metal deposit. If motors are to be run by an alternating current, a special type of motor is generally used, which is very different from the ordinary direct-current motor. The real advantage in the use of alternating currents is **economy of transmission.** This is made possible by a simple and efficient machine known as a **transformer.**

366. What a transformer does. It must be kept in mind that a transformer is primarily a **voltage changer** and that it does *not* change alternating to direct current. Perhaps we can best show what a transformer does by describing a **bell-ringing transformer,** which enables us to take power from the ordinary a-c. lighting circuit and to use it for operating bells, buzzers, door openers, and the like. This little device changes the 110 volts of a lighting circuit down to the 5, 10, or 15 volts which are needed for ringing bells.

Figure 409 shows the exterior and interior construction of one type of bell-ringing transformer. The terminals *A* and *B* are connected through fuses to the 110-volt a-c. circuit and are called the **primary terminals.** The terminals *x* and *y* are the **secondary terminals** and

will give 10 volts when the primary voltage is 110 volts. When we examine the interior construction, we are surprised to find it so simple — merely an iron core and two coils of wire. The core *C* consists of thin sheets of annealed steel stamped out in the proper shape to give a closed magnetic circuit. The primary coil *P* of enamel-covered wire has about 880 turns, and the secondary coil *S* has approximately 80 turns.

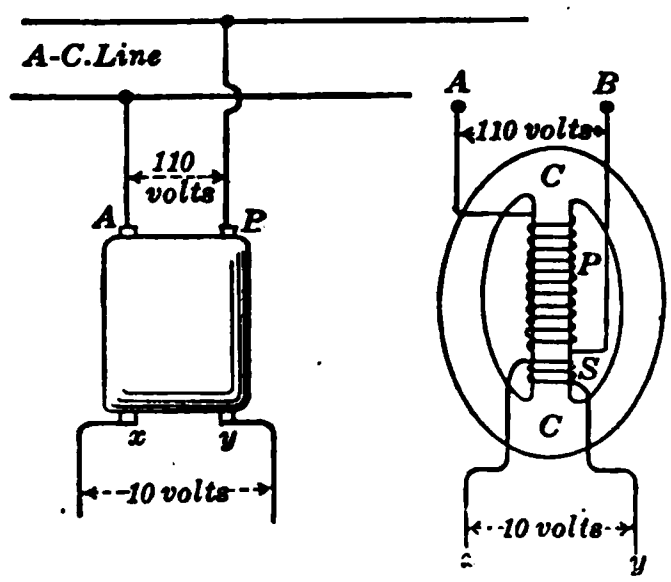

Fig. 409. Bell-ringing transformer with diagram of interior construction.

367. The principle of the transformer. In any transformer there are two coils side by side on a common iron core. When an alternating current is set up in one coil, called the **primary**, it magnetizes the iron core, causing surges of magnetic flux first in one direction and then in the opposite direction. Since this magnetic flux passes through the second coil, called the **secondary**, as well as the first, it induces an alternating current in the secondary. Since the same number of lines of force pass through both coils, **the volts per turn are the same.** Therefore, *the total voltage in the primary coil is to the total voltage in the secondary coil as the number of turns in the primary is to the number of turns in the secondary.* This may be expressed in the following equation:

$$\frac{\text{Voltage on primary}}{\text{Voltage on secondary}} = \frac{\text{turns of primary}}{\text{turns of secondary}}.$$

Thus we see that the alternating-current power is transferred from the primary to the secondary by means of the magnetic flux in the iron core.

368. Ordinary distributing transformer. Since the voltage of the transmission lines in the street is usually about 2300 volts, it is necessary to transform it, or "step it down," to 115 volts in order to use it safely in private houses. In such a transformer the high-tension coil, consisting of many turns of small

wire, would be connected to the 2300-volt circuit, and the low-tension coil, consisting of a few turns of large wire, would be connected with the lamp circuit of the house. In this case the high-tension, or primary, coil must have 20 times as many turns as the low-tension, or secondary. But the secondary coil must be made of larger wire than the primary coil, because the secondary current is about twenty times the current taken by the primary. Thus the transformer delivers the same amount of energy which it receives, except for a small amount (from 2 to 5 per cent) which is lost as heat in the transformer. The efficiency of a transformer is therefore very high—from 95 to 98 per cent.

Transformers are built in two general types: (*a*) the **core type** (Fig. 401, *A*), in which the coils are wound around two sides of a rectan-

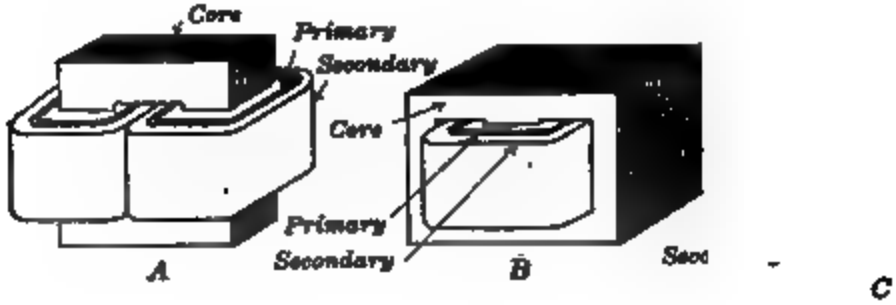

Fig. 410. Three types of transformer; *A*, core type; *B*, shell type; *C*, H-type.

gular iron core, and (*b*) the **shell type** (Fig. 410, *B*), in which the iron core is built around the laminated coils. In both these types the cores are built up of thin sheets of annealed silicon steel.

The most modern type is really a modification of the core type, with which are combined many of the advantages of the shell type. It has the windings, or coils, on one leg of the core, while the other leg is divided into four parts, symmetrically placed around the center leg, on which the coils are placed, as shown in figure 410, *C*. To keep the coils insulated, the transformer is put into an iron case and surrounded with oil. These iron cases (Fig. 322) are commonly attached to poles near houses wherever alternating current is used for lighting purposes.

369. Uses of transformers. In electric-light stations it is common practice to use alternators to generate electricity at

2300 volts. The current is transmitted at this high voltage to the various districts, where it is transformed, or "stepped down," to 115 volts for use in lighting houses. Another important use of step-down transformers is to furnish large currents at very low voltage for electric furnaces and electric welding.

To illustrate this, we may wind a turn or two of very large copper wire around the core of a small step-down transformer (Fig. 411) and connect its primary to a 110-volt a-c. circuit (if one is available). The ends of the large wire should be attached to a pair of iron nails. If, when the current is on, the tips of the nails are brought together, they get red hot and can be welded.

Fig. 411. Experimental step-down transformer used for welding.

The adjoining rails of a car track are often welded together in this way. A heavy current is required for a short time, and is obtained by using a step-down transformer, in which the secondary consists of only one or two turns, made of very large copper bars. The ends of this secondary are clamped to the rails which are to be welded, one on each side of the junction.

370. Long-distance transmission of power. By the use of alternating currents of high voltage, even up to 220,000 volts, power is now transmitted very long distances. For example, electric power is generated in hydroelectric power plants in the Sierra Nevada Mountains of California, and transmitted about 250 miles to Los Angeles. To understand why the economical transmission of electricity demands such high voltage, we should remember that the power transmitted depends on the product of voltage and current strength. Evidently, then, if we can make the voltage high, the current can be low. But a smaller current means smaller losses in transmission; for they are due to the heating effect of the electric current, and we have already seen that this varies as the *square* of the current.

It is not an unusual thing to see three or six copper cables, each about $\frac{3}{4}$ of an inch in diameter, suspended about 75 feet above the ground on steel towers (Fig. 412) and to learn that those wires are carrying 40,000 kilowatts of electrical energy

Hydroelectric power plants are being developed all over the country. For example, at Niagara, power plants are generating electricity, raising the voltage to 60,000, and transmitting some of the enormous energy available at the Falls to distant cities like Buffalo, Rochester, and Syracuse. Just outside the city limits there are substations where the voltage is reduced to about 2000, and then it is distributed to factories and for general use in lighting and traction. Before the current actually enters the buildings, the voltage is again stepped down to 220 or 110 volts.

Fig. 412. High-voltage long-distance transmission lines.

At the power stations are **step-up transformers**, which receive electric power at from 2300 to 11,000 volts and step it up to from 50,000 to 220,000 volts for the transmission lines. In this process no power is gained in the transformer, since electric power depends on the product of voltage and current. We may *multiply* the voltage perhaps 10 times, but at the same time we *divide* the current by a little more than ten, so that we always lose some power. In very large transformers the *insulating* oil has to be water-cooled; and for high-voltage installations,

the out-of-doors type of transformer and switch (Fig. 413) is largely superseding the indoor type.

Fig. 413. Out-of-doors transformers in which the oil is water-cooled.

371. Eddy currents. We have seen that the cores of transformers are made of soft-iron or mild-steel sheets stamped out in the desired shape and then assembled. In the construction of induction coils, the cores are made of soft-iron wires, which are put together in a bundle. If we examine the armature of a dynamo, we find that the iron drum is made of laminæ (sheets) of mild steel which are stamped out in the shape of disks with notches around the edge (Fig. 414), and then assembled on a framework called the " spider," and mounted on the shaft. In all these cases the sheets or wires are insulated from each other by a coating of shellac, which eliminates what are sometimes called Foucault, or **eddy currents.**

We have already seen, in studying the generator, that when any conductor cuts lines of force, an induced electromotive force tends to send a current along the conductor. In the generator copper wires are provided to carry this current; but these wires are wound on an

iron core, and if this core is itself an electrical conductor, an induced e.m.f. will be set up in it as it revolves in the magnetic field. This induced e.m.f. would send electric currents through certain portions of the core. These so-called eddy currents would soon heat the core, and would also retard the motion of the armature and waste power. To reduce these currents to as small a value as possible, the core is laminated in such a way that the insulation is transverse to the direction in which the eddy currents tend to flow.

Fig. 414. Laminated core of a generator armature.

372. Use of eddy currents in damping. To show that eddy currents tend to retard the motion of a conductor in a magnetic field, we may set up between the poles of a strong electromagnet a pendulum made of thick sheet copper (Fig. 415). If the magnet is not excited, the pendulum swings back and forth as any pendulum does; but when we throw on the current in the magnet, the copper pendulum cannot swing through the magnetic field, and is instantly checked. The eddy currents set up in the copper tend to retard the motion of the pendulum, much as if it were swinging in thick sirup.

Fig. 415. Damping of the copper pendulum by eddy currents.

This effect is very useful in stopping the vibrations of the moving coil of a d'Arsonval galvanometer (section 303). The wire is usually wound on a light copper or aluminum frame, and the eddy currents in this metal frame check its swinging. Such a galvanometer is called "dead-beat." We shall see, in section 383, that the same principle is used to check the rotation of a watt-hour meter.

Questions and Problems

1. What limits the voltage which it is practicable to use on high-tension transmission lines?

2. Why are the cables for long-distance transmission sometimes made of aluminum instead of copper?

3. If a step-down transformer is to be used to change the voltage from 1100 to 220, what must be the ratio of turns of wire on the primary and secondary coils?

4. A transformer has 1000 turns on the primary and 50 turns on the secondary, and the primary current is 20 amperes. About how much is the secondary current?

5. What generates the heat required to weld the nails in the experiment shown in figure 411? Why does not the copper wire *S* melt, as well as the tips of the nails?

PRACTICAL EXERCISES

1. Comparative cost of a bell-ringing transformer and dry cells. Find the cost of the transformer and the cost of operating it including "interest and depreciation." Find the cost of operating doorbells on dry cells. Which system gives the better service?

2. Making a small transformer. Excellent directions will be found in *John D. Adams's* Experiments with 110-volt Alternating Current (Modern Pub. Co., N. Y.).

373. Impedance. If we measure the resistance of the primary coil of a bell-ringing transformer, we find it to be perhaps 13 ohms; when we place the transformer on a 110-volt alternating-current line, we might expect to get $\frac{110}{13}$, or 8.5 amperes. But an a-c. ammeter would actually show only 0.05 amperes to be flowing in the primary coil. Evidently then there is something besides the resistance which is checking the alternating current. This something which checks the alternating current is called **impedance**. In this case the impedance is $\frac{110}{0.05}$, or 2200 ohms. Thus we see that a coil which would be quickly burned out on a 110-volt d-c. line uses practically no current on a 110-volt a-c. line.

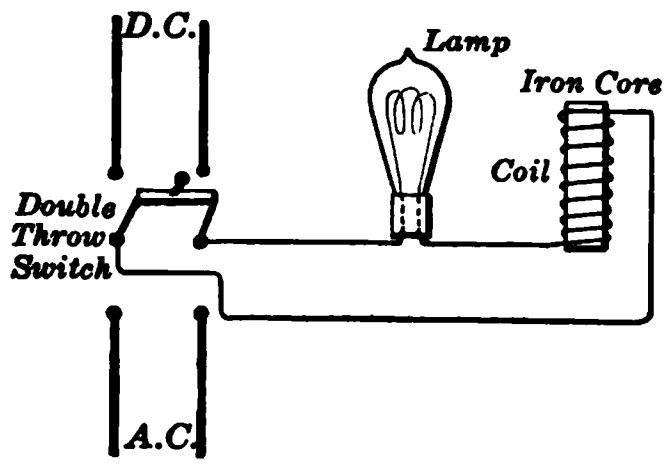

Fig. 416. Lamp connected in series with inductance on d-c. and a-c. circuits.

Let an incandescent lamp be connected in series with a coil which has a removable iron core, as shown in figure 416.

Remove the core and let a direct current be passed through the coil and the lamp. We see that the lamp burns brightly. If we insert the iron core inside the coil, the brilliancy of the lamp is not in the least diminished. If we now remove the core and connect the coil and lamp to an alternating-current supply of the same voltage as the direct current, the lamp becomes *dim;* and if the iron core is again inserted in the coil, the dimming effect is still more strikingly shown.

This remarkable choking down of the alternating current is caused by the inductance of the coil, which sets up an opposing e.m.f., or **back voltage**, whenever the current changes.

374. Power in an alternating-current circuit. In a direct-current circuit, as we have already learned, the power in watts is always equal to the volts times the amperes. In an alternating-current circuit which is non-inductive, such as that of an ordinary incandescent lamp, the same rule holds true. But in an inductive circuit, such as the primary of a bell-ringing transformer, we find that the power, as measured by a wattmeter, is less than the product of the volts times the amperes. *This fraction which the true power is of the apparent power* (product of volts times amperes) *is called the power factor.*

A-c. power (watts) = volts × amperes × power factor.

FOR EXAMPLE, we should expect the wattmeter in the case of the transformer just described to read 110×0.05, or 5.5 watts; but it really indicates only 4 watts. Thus the power factor of the transformer primary coil is

$$\frac{\text{True power}}{\text{Apparent power}} = \frac{\text{4 watts}}{\text{5.5 volt-amperes}} = 73 \text{ per cent.}$$

If a circuit contains resistance only, its power factor is 100 per cent; but in an inductive circuit the power factor is less than 100 per cent. The greater the amount of inductance in a circuit, the lower will be the power factor. In practice the average value of the power factor on a commercial circuit with both lamps and motors is about 85 per cent.

375. Condenser on an alternating-current circuit. In telephone sets, the ringer, or bell, is operated by an alternating current, and a condenser is connected in series with the bell

(Fig. 417) to permit an alternating current to pass through it and to prevent the flow of the direct current used for talking.

If we connect an incandescent lamp in series with a condenser (Fig. 418) to a d-c. line, the lamp is not lighted because the circuit is open between the plates of the condenser. But when we connect the same circuit to an a-c. line, the lamp glows, even though the circuit is open between the plates of the condenser.

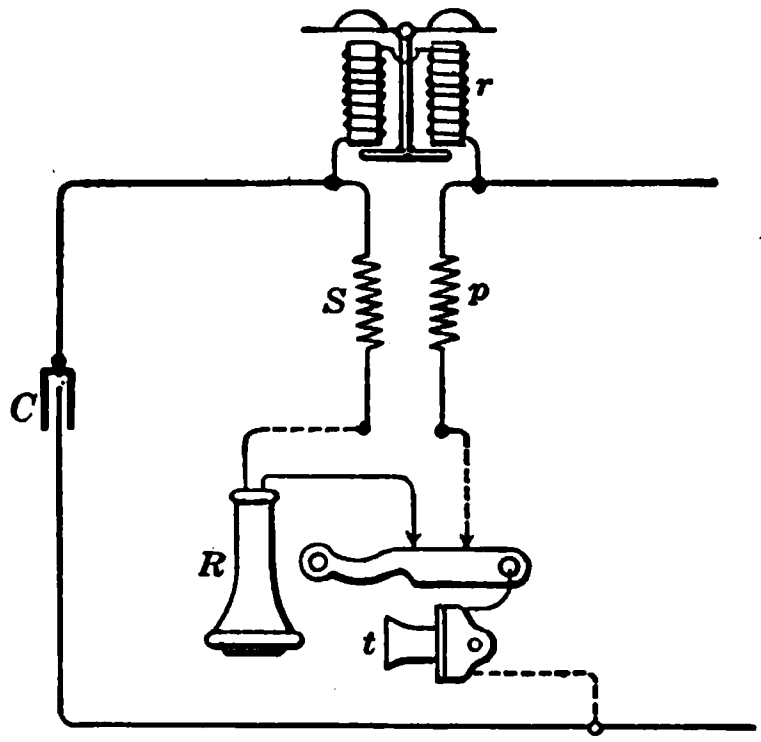

Fig. 417. Diagram of connections in a desk telephone set used with common battery. *C* is a condenser.

The action of a condenser on an a-c. circuit is such, that although no electricity flows *through* the condenser, it does flow *into and out of* the condenser. It is this surging back and forth of the electricity which causes the lamp to glow. If we reduce the size of the condenser, no glowing is observed, because the condenser does not have sufficient **capacity**.

We may picture the action of a condenser on an a-c. circuit by comparing it to a box with a diaphragm in a pipe line, as shown in figure 419. This box is divided into two compartments *C* and *C* by means of a rubber diaphragm *D*, and the two compartments are connected to a pump *P*. This reciprocating pump displaces the water, first in one direction, as the piston moves upward, then in the other, as it moves downward. Thus the surging of the water back and forth subjects the diaphragm to a mechanical stress.

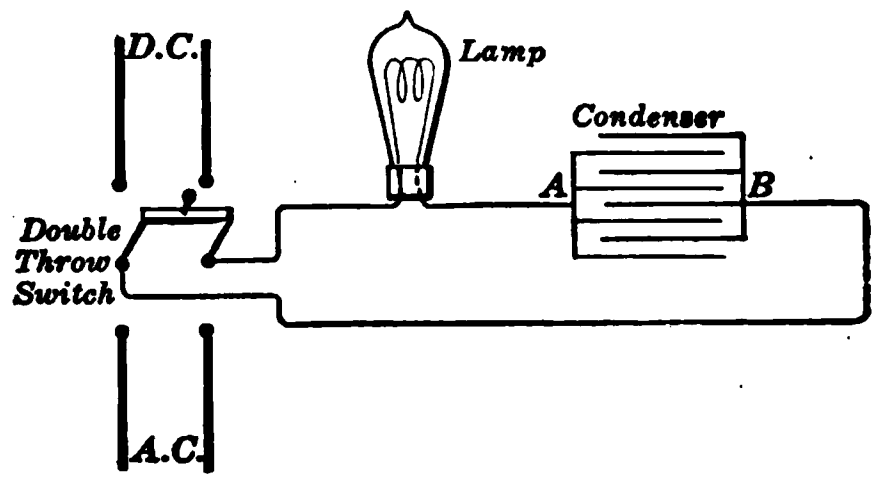

Fig. 418. Lamp connected in series with condenser on d-c. and a-c. circuits.

The pump corresponds to an a-c. generator, the two compartments

of the box to the two sets of plates in the condenser, and the diaphragm to the dielectric of the condenser.

When the alternating current moves one way in the circuit, one set of plates in the condenser becomes positively charged, the other negatively. When the current reverses, the charges on the condenser plates reverse. In the ordinary lighting circuit this process of reversing takes place 120 times each second, so that electricity flows rapidly into and out of the condenser. Condensers play a very important part in radio telegraphy.

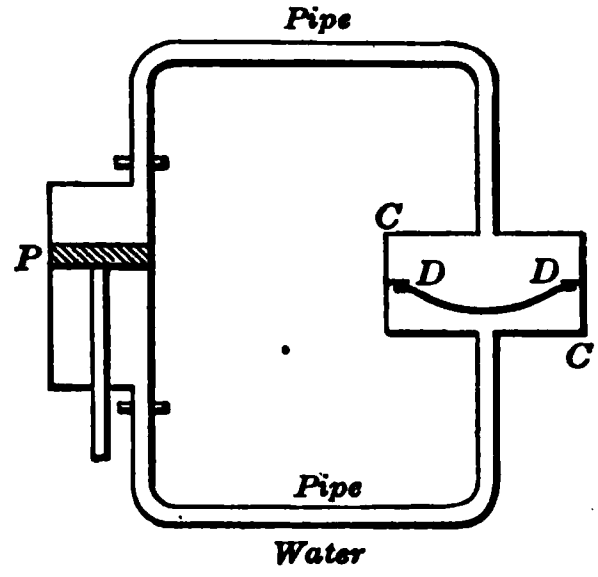

Fig. 419. Mechanical analogue of a condenser on an a-c. circuit.

PROBLEMS

1. A certain transformer has a primary coil with a resistance of 260 ohms. What current will it take on a 115-volt d-c. line?

2. The same transformer on a 115-volt a-c. line draws 0.0575 amperes. What is its impedance?

3. The same transformer, when connected with a wattmeter, takes 4.5 watts. What is the power factor of the exciting current?

4. A certain transformer takes 7.5 watts from a 110-volt a-c. line at 60-per-cent power factor. What current does it draw?

5. How much power is consumed by a coil on a 230-volt a-c. line, when the power factor is 75 per cent and the impedance of the coil is 45 ohms?

376. Alternators. When a coil of wire is rotated in a magnetic field, we have seen (section 339) that the current changes its direction every half-turn. That is, there are two **alternations** for each revolution in a bipolar machine. In a direct-current generator this alternating current is rectified by the use of a commutator. In the alternating-current generator, called an **alternator**, the current induced in the armature is led out through slip rings, or collecting rings (Fig. 369).

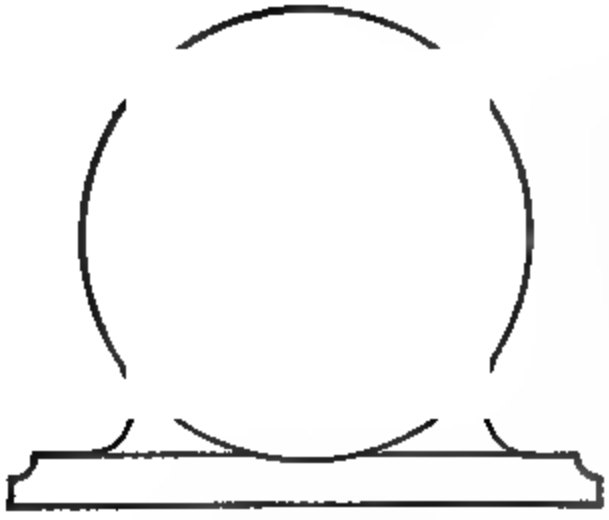

Fig. 420. Diagram of a revolving field and stationary armature.

The field magnet of an alternator is usually an electromagnet which is excited by direct current from a small auxiliary generator, called the **exciter.**

Since it is only the *relative* motion of the armature windings and field magnet which is essential in any generator, large alternators are usually built with a **stationary armature** and a **revolving field.** The revolving projecting poles (*N*, *S*, *N*, *S*, in figure 420) sweep past the armature wires, which are placed in slots around the inner periphery of the stationary structure *A*. The direct current for exciting the field coils is led in through brushes which rub on two insulated metal rings. The alternating current is led directly from the windings of the stationary armature through cables to the switchboard. The great advantage that the stationary armature has over the rotating armature is that the current is generated in conductors which do not move and can therefore be delivered to the external circuit without any sliding contacts. It is also easier to construct the proper insulation necessary for high voltages. Figures 421 and 422 show the revolving field and stationary armature of a commercial alternator which is driven at high speed by a steam turbine. Some of these have a speed of as much as 3600 r. p. m. Figures 423 and 424 show the same parts of an alternator which is driven at slow speed by a reciprocating steam engine or a water wheel.

377. Cycles and phase of alternating currents. When a conductor is moved past a magnetic *N*-pole, the induced e.m.f. is in one direction; and when it moves past an *S*-pole, the induced e.m.f. is in the opposite direction. This can be best represented by the curved line

Fig. 421. Partly wound revolving field (4 poles) of high-speed alternator to be used with steam turbines.

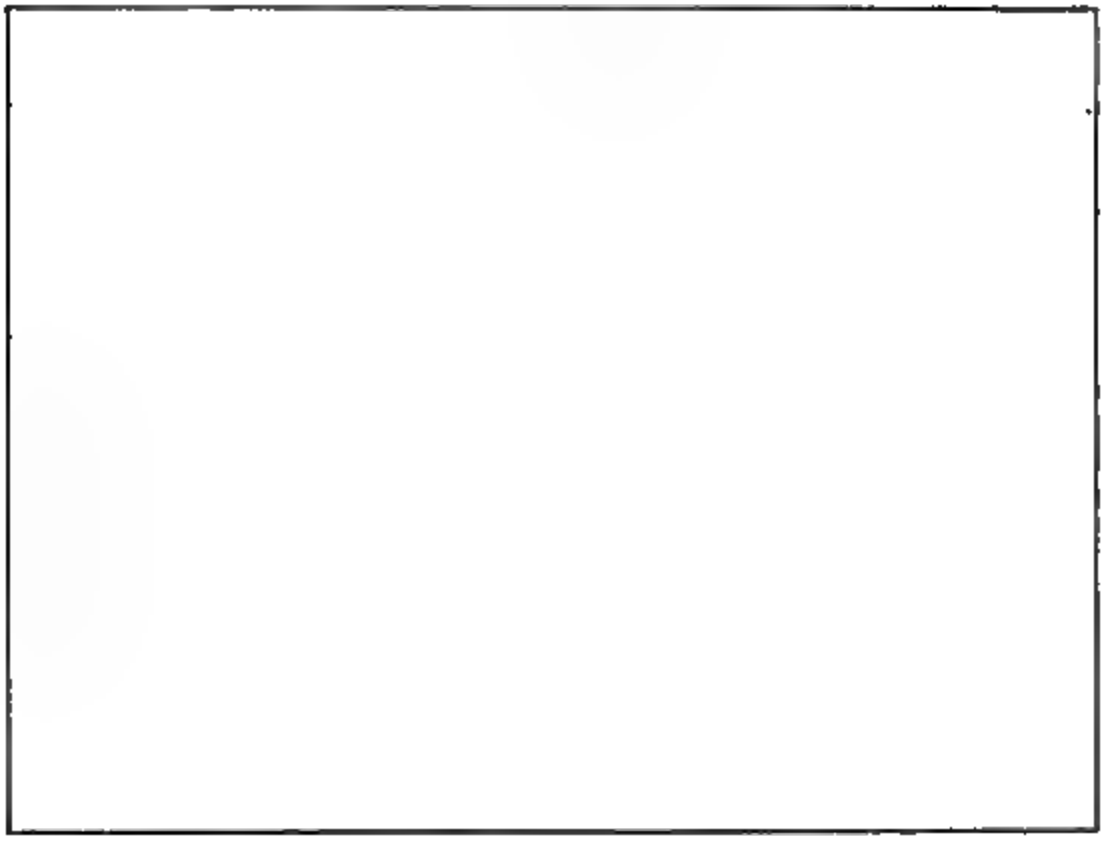

Fig. 422. Stationary armature of the alternator shown in Fig. 421.

Fig. 424. Stationary armature for the rotating field shown in Fig. 423.

Fig. 423. Revolving field with 60 poles used with reciprocating steam engines and water wheels.

shown in figure 425. One complete wave is produced when a wire moves through a complete revolution in a bipolar machine, or from a north pole past a south pole to the next north pole in a multipolar machine, and is called a **cycle**.

Fig. 425. Curve of alternating e.m.f.

In practice it is common to use for lighting an alternating current whose **frequency** is 60 cycles per second; while for power purposes 25-cycle currents are common.

A complete wave, or cycle, is called 360 **electrical degrees** by analogy with the complete revolution of a bipolar generator. Any point or position in the cycle is spoken of as a certain **phase**. When, for example, the cycle is half completed, the phase is said to be 180 degrees, and when the cycle is one fourth completed, the phase is 90 degrees. Two alternating currents of electricity, flowing in branch circuits, may be at different phases, as represented in figure 426, where one curve represents the current in one branch and the other curve the current in the other branch. In the case shown, one current is said to lag behind the other by 90 degrees.

Fig. 426. Curves of two alternating currents which differ in phase 90°.

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Experiments show that, in a circuit having inductance, an alternaing current is always retarded a certain amount behind the alternating voltage which sets it up. The alternating current lags behind its voltage.

Fig. 427. Diagram of a single-phase alternator, showing revolving field (8 poles) and stationary armature.

378. Single and polyphase circuits. If we connect all the stationary

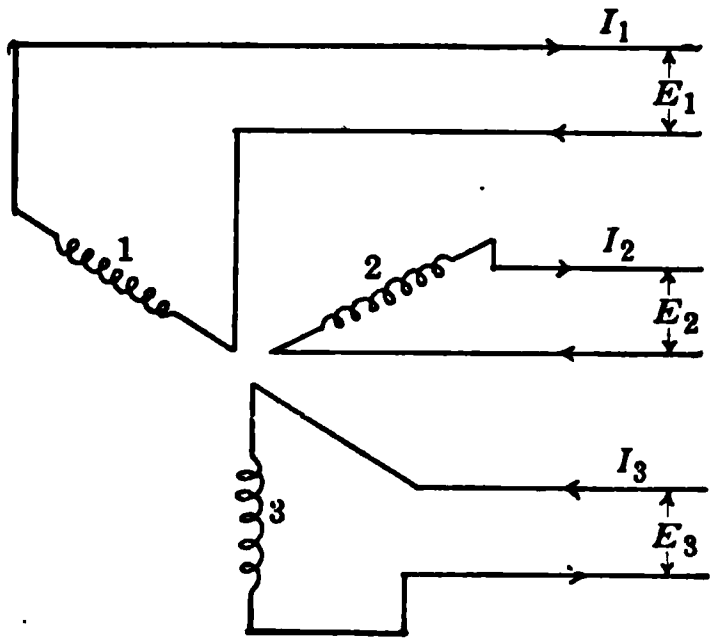


Fig. 428. Diagram of 3-phase alternator with six line wires.

armature coils of a generator in series, and revolve the field as shown in figure 427, a **single-phase** alternating current is produced, whose *frequency* we can determine by *multiplying the number of revolutions per second of the rotor by the number of pairs of poles*. To make use of this current for any purpose, such as electric lighting, we have simply to cut this armature circuit at any convenient point and connect the ends directly to the mains. It will be noticed that there are as many coils on the armature as there are poles in the field magnet of the single-phase machine.

It has been found more economical of space to have more than one coil for each pole of the field; and so we have **two-phase** and **three-phase machines**, in which there are two or three sets of coils on the armature. In the three-phase machine, which is the type most used to-day, the three sets of armature coils may each be used separately to furnish electricity for three separate lighting circuits, as shown in figure 428.

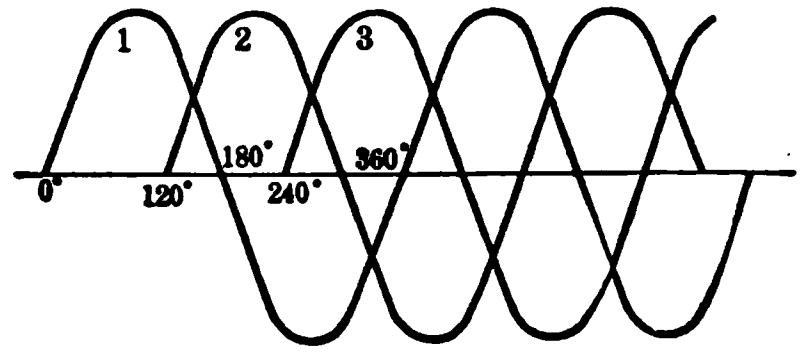


Fig. 429. Curves of alternating currents in a 3-phase system.

The currents in the three circuits differ in phase by 120 degrees (Fig. 429). It will be seen that the currents are such that at any instant their sum is zero.

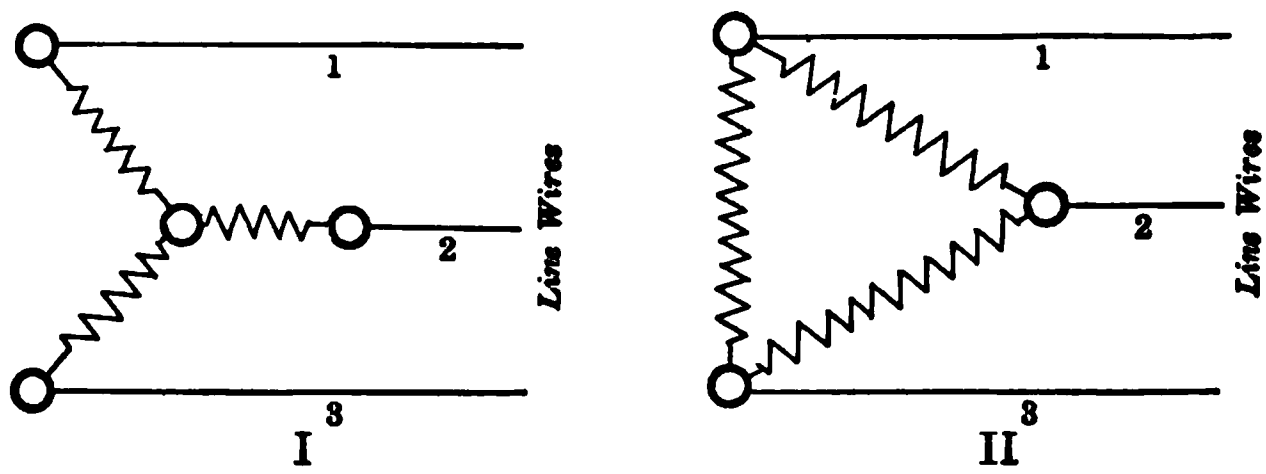


Fig. 430. (I) The star or Y-connection and (II) the delta or Δ-connection on a three-phase system.

Fig. 431. Two 30,000-kilowatt alternators directly connected to steam turbines in Delaware Power Station of the Philadelphia Electric Company.

Electrical engineers have invented two methods of connecting apparatus of any sort to a three-phase circuit, so as to have only three live wires instead of six, and thus to save wire. They are the star or Y-connection shown in figure 430 (I) and the delta or △-connection shown in figure 430 (II). Most alternators have their coils, Y-connected; and a-c. motors are sometimes connected in star and sometimes in delta.

379. Use of alternators. The revolving-armature type of alternator is generally used only in small electric-lighting stations. Large alternators of the revolving-field type are usually mounted on the same shaft (direct-connected) with the driving engine or water wheel. Alternators of very large capacity are now extensively used with steam turbines. They can be comparatively small in size because they are driven at such high speed. These alternators have a revolving field of only a few poles (sometimes only two) and a wide air gap between the armature core and the field poles. Figure 431 shows a 30,000-kilowatt alternator mounted on the shaft of a steam turbine. In high-tension transmission, the three-wire three-phase system is commonly used.

QUESTIONS

1. How can the engineer at the power house control the frequency of an alternating current?

2. How many revolutions per minute will an 8-pole machine have to make to give a 60-cycle current?

3. What objection is there to using a 25-cycle current for lighting purposes?

4. Draw a diagram to show two alternating currents which differ in phase by 45 degrees.

5. How much do the two currents generated by a two-phase alternator differ in phase?

380. Alternating-current motors. An a-c. generator can be run as a motor, provided it is first brought up to the exact speed of the alternator which is supplying current to it and put in step with the alternations of the current supplied. Such a

machine is called a **synchronous motor.** Since it is not self-starting, it is not convenient for general use, but is used in substations to drive d-c. generators.

An ordinary series motor, by certain modifications in its design, can be made to operate on either d-c. or a-c. systems. These so-called a-c. **commutator motors,** or **single-phase series motors,** are coming into use for electric cars and locomotives

(*b*)

Fig. 432. An induction motor: (*a*) rotor and (*b*) stator.

when an alternating current is used. They are also to be found, in very small sizes, on electric fans and on vacuum cleaners. They are labeled "A-C. or D-C." on the name plates.

The a-c. motor most frequently used is the **induction motor.** The distinctive features of this motor are that the stationary winding, or "stator" (Fig. 432 *b*), sets up a rotating magnetic field, and that the rotating part of the motor, or "rotor," is built on the plan of a squirrel cage (Fig. 432 *a*). These will be discussed in turn.

381. Rotating magnetic field. To produce a rotating field, we shall suppose that we have two alternating currents of the same frequency,

but differing in phase by 90 degrees (Fig. 433), and that we connect them to two sets of coils wound on the inwardly projecting poles of a circular iron ring, as shown in figure 434.

When the current in line 1 is at a maximum, it will be seen from the curves (Fig. 433) that the current in line 2 is zero. The poles A and A_1 are magnetized, while the poles B and B_1 are unmagnetized. The magnetic flux goes from N to S, as shown by the arrow. One eighth of a cycle (45 degrees) later, current 1 has decreased to the same value as that to which current 2 has increased. The four poles are now equally magnetized, and the magnetic flux takes the direction of the arrow shown in II. One eighth of a cycle (45 degrees) later, current 1 ha dropped to zero and current 2 is at a maximum. This means that the poles A and A_1 are unmagnetized, that the poles B and B_1 are magnetized to the maximum, and that the flux passes from N to S as shown by the arrow in III. If this process is continued at successive instants during a complete

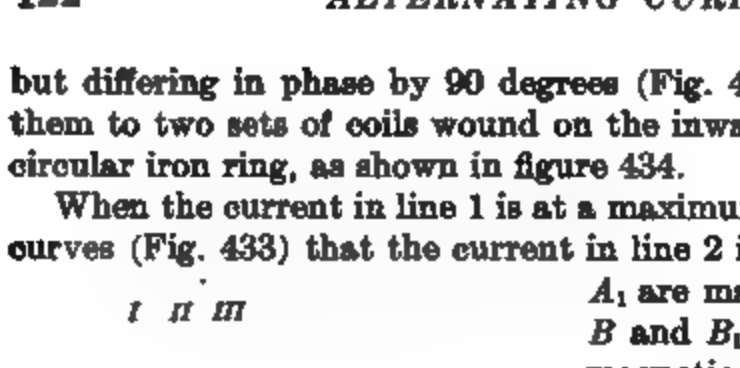
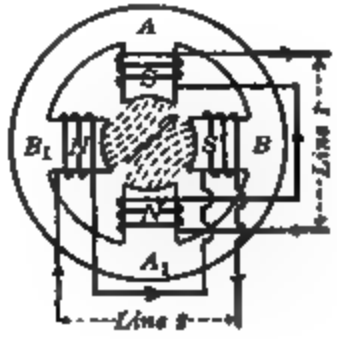


Fig. 433. Curves of two alternating currents which differ in phase by 90°, with arrows showing magnetic field.



I II III

Fig. 434. A rotating magnetic field produced by two currents 90° apart.

cycle of change in the alternating currents, we shall find that the arrow makes a complete revolution. This produces a **rotating field**, and would cause a magnet to rotate with the field. We should then have a little two-phase a-c. motor.

Figure 435 shows a working model which demonstrates the rotating field produced by a two-phase a-c. system (right) and that produced by a three-phase a-c. system (left). Figure 432 (*b*) shows how the stator frame of a practical motor is constructed.

382. The rotor of an induction motor. The rotating magnet can, of course, be replaced by an electromagnet, which is excited by a direct current from some outside source. The rotor of a commercial a-c. motor is, however, much simpler. It consists of an iron core, much like the core of a drum armature, with large copper bars placed

Fig. 435. Working model to demonstrate the rotating field produced by two-phase (right) and three-phase (left) alternating currents.

in slots around the circumference and connected at both ends to heavy copper rings. This is called a **squirrel cage rotor** (Fig. 432 (*a*)).

When a rotor is placed in a rotating magnetic field, the conductors on the two sides and the rings across the ends act like a closed loop of wire, and a large current is induced, even though the rotor has no electrical connection with any outside circuit. This large induced current makes a magnet of the iron core, and the field, acting on this magnet, drags it around.

The rotor can never spin quite as fast as the magnetic field. If it did, there would be no cutting of lines of force, no currents would be induced, and there would be no power available to drive the rotor against its load.

A squirrel-cage rotor is simple and strong, and needs only to be kept cool. This is done by air circulated through the core by fan blades. The assembled machine is strong, compact, and almost "fool-proof." For these reasons the induction motor is finding a wide field of usefulness in shops and factories, and even on electric locomotives.

383. Watt-hour meter. Every user of electricity is interested in the **recording watt-hour meter**, which records on dials, like those of a gas meter, the number of kilowatt hours of electricity consumed. It is on the readings of this instrument

that the monthly bills are based. Figure 436 shows the Thomson form of watt-hour meter. It is really a little shunt motor, the armature of which turns at a speed proportional to the rate at which electrical energy is passing through the meter. The armature drives the recording dials. The field of the instrument is made by stationary field coils which are connected in series with the line. The field strength is therefore proportional to the current flowing in the main line. The armature is connected across the line, and takes a current proportional to the voltage across the line. Therefore, the torque which turns the armature is proportional to the product of the current and the voltage; that is, to the watts in the line.

Fig. 436. Diagram of Thomson's watt-hour meter.

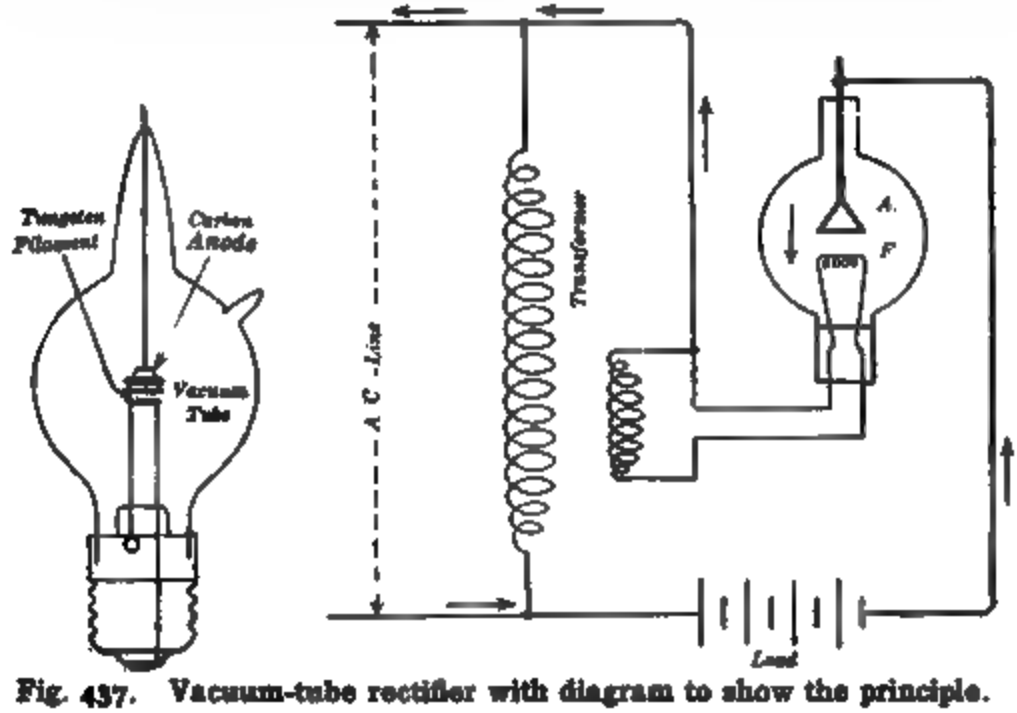


Fig. 437. Vacuum-tube rectifier with diagram to show the principle.

The inertia of such a machine would make it run too fast, or fail to stop when the current stopped, if it were not for the electric damping caused by the rotation of an aluminum disk

between the poles of permanent magnets. The eddy currents generated in the disk tend to retard its motion.

This type of watt-hour meter can be used on either a d-c. or an a-c. circuit.

384. Converting alternating current into direct current. For certain purposes, such as charging storage batteries, it is absolutely necessary to use a unidirectional current. The method of converting alternating current into direct by means of a motor-generator (that is, an a-c. motor connected to a d-c. generator) is used for large power purposes. But for charging automobile batteries, the **vacuum-tube rectifier** ("Tungar") is much more convenient. While this type of rectifier (Fig. 437) gives a unidirectional current, yet it does not give an absolutely steady current.

It consists of an evacuated glass bulb containing a tungsten filament *F* heated to incandescence by an alternating current, and has a carbon electrode *A* introduced through the top of the bulb. The bulb itself is filled with inert gas at low pressure. The tungsten filament is connected in the secondary circuit of a transformer, which is part of the outfit, and when heated to incandescence emits electrons (negative electricity). If this filament is negative with respect to a near-by anode, the rarefied gas in the bulb is ionized and thus becomes a conductor of electricity. The filament is also connected to one terminal of the a-c. line, and the graphite (carbon) electrode *A* is connected to the other terminal. During the half-cycle in which the graphite electrode is positive and the filament is negative, current passes through the bulb, because of the ionizing action of the electrons. During the other half-cycle, when the graphite electrode is negative, the gas remains nonconducting, because the electrons cannot escape from the filament. Thus *the current passes through the valve during each alternate half-cycle from the graphite to the tungsten filament.* We have, then, in the circuit of the bulb a pulsating unidirectional current, which is suitable for charging storage batteries.

Practical Exercise

Making an electrolytic rectifier. A simple form of rectifier consists of four jars, each containing a solution of ammonium phosphate, a strip of sheet lead, and a strip of aluminum. See *Adams's* Experiments with 110-volt Alternating Current (Modern Pub. Co.).

SUMMARY OF PRINCIPLES IN CHAPTER XVIII

In a transformer:

$$\frac{\text{Voltage on primary}}{\text{Voltage on secondary}} = \frac{\text{turns of primary}}{\text{turns of secondary}}.$$

In an alternator:

Frequency = revolutions per second × number of pairs of poles.

A-c. power = amperes × volts × power factor.

Power factor is usually less than one.

QUESTIONS

1. The iron case of a transformer is often corrugated. Why?

2. Why must the "dielectric strength" of the oil used in transformers be carefully tested?

3. In long-distance transmission of power by high-tension lines, the wires are often supported on steel towers 75 feet above the ground, and the company gets a right of way or a strip of land 100 feet wide over which to run its wires. Why these precautions?

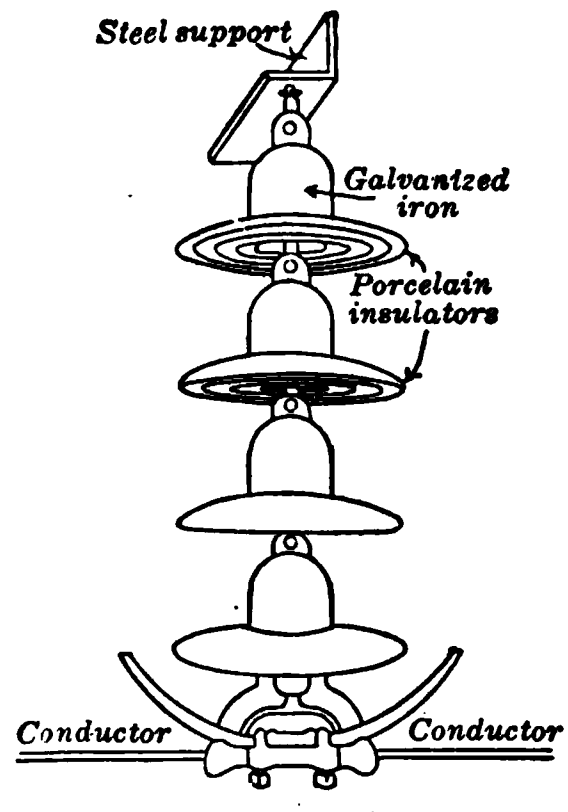


Fig. 438. Suspension-type of insulator used on high-voltage lines.

4. What is gained by making the armature of a big alternator stationary, and rotating the field?

5. How could an induction coil be used as a step-up transformer?

6. What advantages have steel towers over wooden poles for holding up high-tension wires?

7. What advantages has the suspension-type of insulator (Fig. 438) for high-voltage transmission lines?

8. What type of alternator is used with a reciprocating steam engine? Why?

9. What reasons have led to the fact that a very large percentage (perhaps 95 per cent) of all the electrical power generated in this country to-day in central stations is alternating current?

CHAPTER XIX

SOUND

What makes sound — what carries sound — velocity of sound — water waves — velocity, wave length, and frequency — longitudinal waves — sound waves — loudness and distance — directing sound — finding the direction of sound — reflecting sound — sound in rooms — musical tones — intensity, pitch, and quality — resonators — overtones — photographing sound waves — beats — the musical scale — stringed instruments — wind instruments — membranes — the phonograph.

385. What makes sound? When a bell rings, we see the hammer or clapper hit the bell, and hear the sound which it makes. If we hold a pencil against the edge of the bell just after it has been struck, we find that the metal is moving to and fro very rapidly. When a guitar string is plucked, it gives forth a note which we can hear, and at the same time we can see that the string looks broader than when at rest. We conclude that the string is vibrating or oscillating back and forth. When we strike a tuning fork and hold it near the ear, we hear a note, and if we touch the fork to the lips, we feel its vibratory motion.

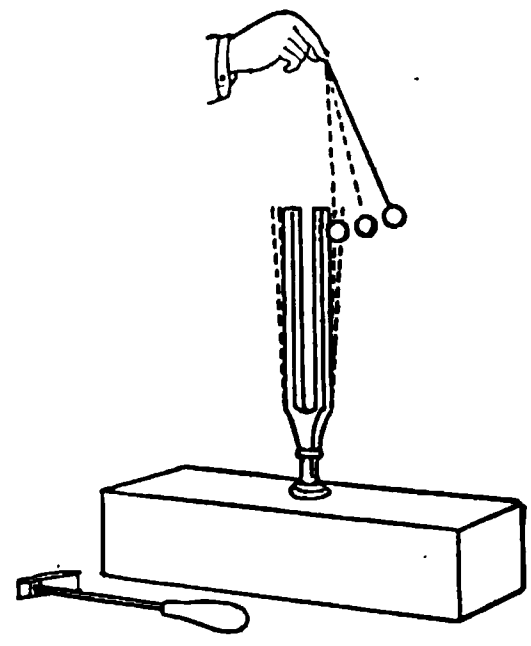


Fig. 439. Vibration of a tuning fork made visible.

To make visible the vibration of a tuning fork, let us touch it to a light glass bubble suspended on a thread (Fig. 439). The bubble is set violently in motion.

Another way to show the vibratory motion of a fork is to attach a point of stiff paper to one prong. Let us set such a fork in vibration and draw a piece of smoked glass under it (Fig. 440). The curve traced is easily made visible by putting white paper behind the glass.

Whenever we look for the source of a sound, we find that something has been set in motion. It may be that something has fallen, a bell has been struck, a whistle has been blown, or someone has shouted; always something has been set vibrating, which has caused the sensation of sound.

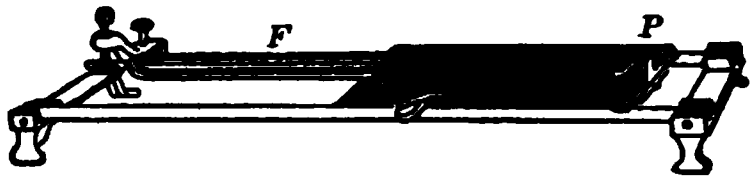


Fig. 440. Curve traced by a vibrating fork on a smoked glass.

386. What carries sound? Ordinarily the air, which is everywhere about us, brings sound to our ears. To make this evident let us try the following experiment.

Let us place an alarm clock on a felt cushion under the receiver of a good vacuum pump, as shown in figure 441. If we set the clock so that the bell rings intermittently, and then pump out the air, we find that the sounds become fainter and fainter. When we let the air in again, the bell sounds as loud as at first. It seems probable that the bell would become quite inaudible if we could get a perfect vacuum, and if no sound were conducted out by the supporting base.

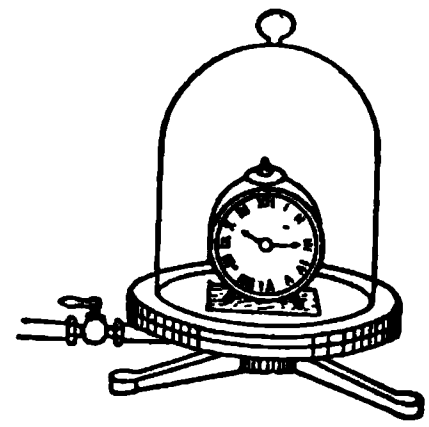


Fig. 441. Sound is not carried through a vacuum.

We know that both heat and light can traverse a vacuum, as in the case of the electric-lamp bulb; but we see from this experiment that sound does not traverse a vacuum.

It can be shown that other gases besides air carry sound, and that liquids and solids are even better carriers of sound than gases. For example, if one holds one's ear under water while some other person hits two stones together a short distance away, the sound is heard very distinctly. It is also a familiar fact that one can hear a train a long distance away by putting one's ear

close to the steel rail. Loud sounds, like those of cannon, or of volcanic eruptions, can be heard at a distance of several hundred miles by putting one's ear to the ground.

To show that liquids transmit sound, let us put the stem of a tuning fork into a hole bored in a large cork. If we set the fork in vibration, it is hardly audible; but if we hold it with the cork resting on the surface of a glass of water which stands on a resonating box (Fig. 442), we hear it distinctly. The sounds seem to be coming from the box. This experiment shows that the vibration of the tuning fork is transmitted through the cork and the water to the air in the room.

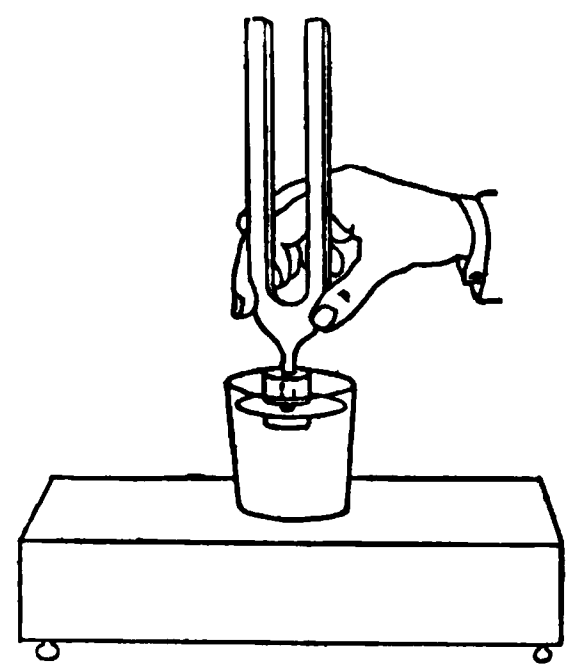


Fig. 442. Sound of fork is transmitted by water to box.

To show that solids transmit sound, we may hold one end of a long wooden stick against a door, and rest a vibrating tuning fork on the other end; the sound of the fork seems to be coming from the door. The wooden stick here serves as the sound carrier and transmits the vibration of the fork to the door.

So we conclude that *solids, liquids, and gases may serve as carriers of sound.*

387. How fast does sound travel? In an ordinary room one is not aware that it takes any appreciable time for sound to travel from its source to one's ears; but in a large hall, or outdoors, one often hears an echo, which shows that sound does take time to travel to a reflecting surface and back. During a thunder shower we hear the roll of the thunder after we see the flash. The farther away the lightning discharge is, the longer the interval between seeing the flash and hearing the rumble. Everyone has doubtless *seen* the steam from a distant whistle, and then later *heard* the whistle. So there is no doubt that sound travels much more slowly than light.

One way to measure how fast sound travels is to have a cannon discharged on a distant hill and measure the time between see-

ing the flash of the cannon and hearing its report. In such an experiment, which was performed by two Dutch scientists in 1823, two cannons were set up on hills about eleven miles apart, and observations were made first from one hill and then from the other, to eliminate the error due to wind. Their result was remarkably near the truth, considering the instruments they had. Since then, several determinations of the velocity of sound in air have been made, which show that at 0° C. and 76 centimeters pressure the *velocity of sound is 1087 feet (or 331 meters) per second.* The speed of sound in water is about 4.5 times the speed in air, and in steel it is more than 15 times as great as in air. It has also been found that the speed of sound in air increases about 2 feet (or 0.6 meters) per second for each degree centigrade rise in temperature. For many practical purposes it is enough to remember that *sound travels in air about 1100 feet per second.*

PROBLEMS

(Assume that the time taken by light to travel ordinary distances is negligible.)

1. A steam whistle is heard 2.6 seconds after the steam is seen. How far away is the whistle? Assume the temperature to be 15° C.

2. A man sees a hammer strike a bell a mile away every 2 seconds. What is the interval between the sounds of the successive strokes?

3. On a hot summer day, when the temperature is 30° C., the flash of a gun is seen 2 miles away. How long after the flash will the report of the gun be heard?

4. A stone is dropped from the top of the Woolworth Building in New York City, which is 750 feet high. The temperature is 68° F. How long before a man on top would hear the sound of the stone as it struck the pavement? (The time includes the time for the stone to fall and for the sound to return.)

5. If an experiment shows that sound travels in water 4814 feet per second at 14° C., how many times as fast does sound travel in water as in air at this temperature?

6. A lightship is equipped with a bell under water and with a foghorn. The captain of a vessel receives the under-water signal in a telephone

receiver (Fig. 443) 4 seconds before he hears the whistle. Assuming that sound travels 1100 feet per second in air and 4800 feet per second in water, compute the distance of the captain from the lightship.

7. If the noon signal is given by a gun 5 miles away, how much allowance must be made when the temperature is 80° F.?

8. A steel rail is struck and the blow is heard through the rail in 0.2 seconds, and then through the air 2.8 seconds later. Assume the temperature to be 20° C. How many feet distant was the blow struck? What was the velocity of the sound in the rail?

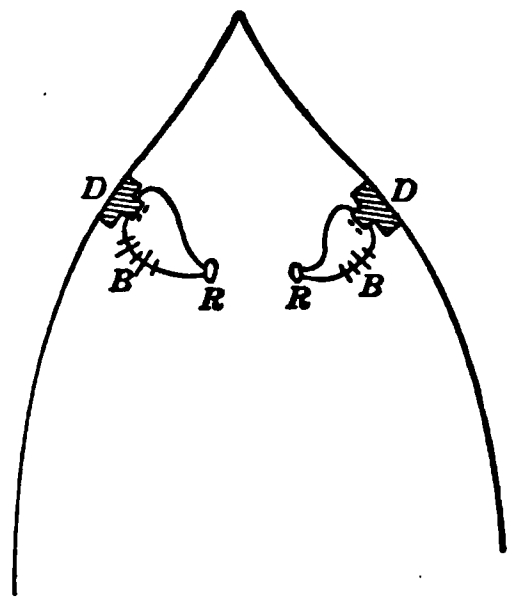


Fig. 443. Submarine telephones attached to a ship's sides.

PRACTICAL EXERCISE

Measuring the velocity of sound. Repeat the experiment described in section 387, using a toy cannon and a stop watch. Get the distance from a large scale map. Record the temperature.

388. Sensation of sound. We have been considering the transmission of "sound" through gases, liquids, and solids, although we know that it is merely a sort of motion which is transmitted. Ordinarily we find it hard to think of sound without thinking of an ear to hear it. Thus we find people asking whether a waterfall in a very remote part of the earth, never visited by man or animal, makes any sound. Evidently there are two things which are called "sound," the **vibrations** and the **sensation** they produce when they strike against the tympanum, or eardrum. The study of what happens in the ear and brain is properly left to physiology and psychology. In physics we shall consider only the vibrations in the air or other transmitting medium, and shall refer to them when we say "sound." In this sense the waterfall makes just as much sound whether there is an ear to hear it or not.

389. Sound is a wave motion. Evidently nothing material (that is, weighable) travels from the source of a sound to the ear; otherwise, how did the sound of the electric bell under

the bell jar get through the glass? This and other facts point unmistakably to the conclusion that what is transmitted is merely a vibration, or **mode of motion**, called a **wave**.

390. Water waves. Since sound waves are usually invisible, we shall start with a study of **water waves**. When a stone is dropped into a smooth pond, a disturbance is produced which extends over the surface of the water in circles centered at the place where the stone struck. The water is pushed down and aside by the stone, forming a circular ridge, which expands into a larger circle and is followed by a second circular ridge, which expands, and so on. The result is that the surface is soon covered with a series of circular crests, which are separated by circular troughs, all moving away from the center of the disturbance.

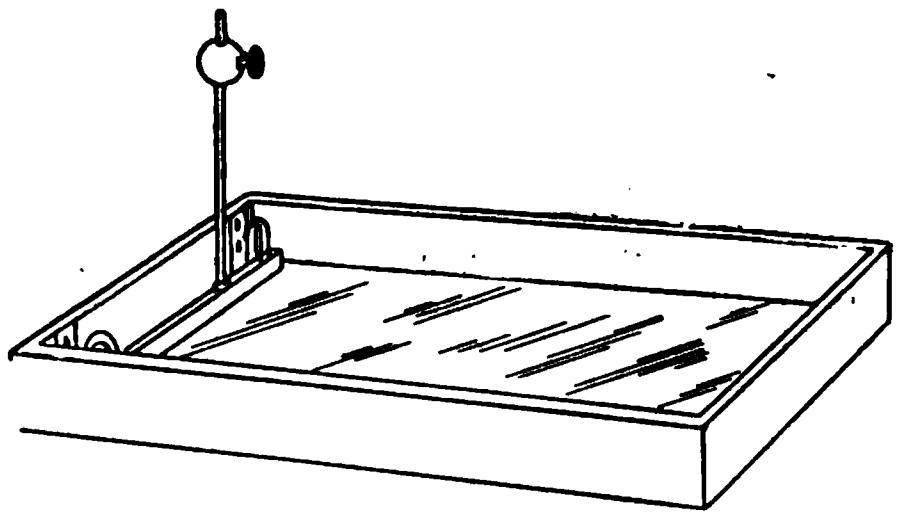


Fig. 444. Apparatus for projecting on the ceiling water waves illuminated from below.

These water waves can be projected on the ceiling by means of a shallow, water-tight box with wooden sides and a plane glass bottom. The box is supported so that light may be thrown on it from below (Fig. 444). Water is poured in to a depth of a quarter of an inch, and the light which passes through the box is received on the ceiling. When a wave is set up in the water, shadows corresponding to the wave fronts will be seen on the ceiling.

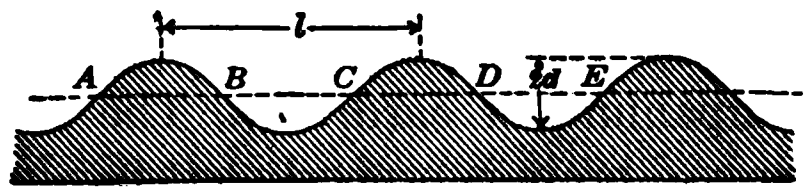


Fig. 445. Cross section of a water wave.

The surface of a water wave may be represented by the curved line shown in figure 445. The stationary points, *A*, *B*, *C*, *D*, etc., are called the **nodes**; the intervening spaces are called the **loops** or **internodes**. The water between nodes oscillates

up and down; when it is up, it forms a crest, and when it is down, a trough. A crest and trough together form a wave, as from A to C, or B to D. The **wave length** l is measured horizontally from any point on one wave to the corresponding point in the next wave. Corresponding points are called points in the same **phase.** The **amplitude** d of the wave vibration is *half* the vertical distance from trough to crest.

391. Relation between velocity, wave length, and frequency. In the case of the waves started by throwing a stone into a quiet pool, we know that while the circular waves grow larger and larger, any particular crest seems to move out radially until it reaches the bank or dies away. The distance which a crest travels in one second is called its **velocity** (v). The number (n) of crests passing a fixed point in one second is called the **frequency.** A moment's thought will show that the relation between the wave length, velocity, and frequency of a wave must be

$$\textbf{Velocity} = \textbf{frequency} \times \textbf{wave length},$$

or

$$v = nl.$$

It should be remembered that it is only the wave form that travels over the surface of the water, not the water particles themselves. Thus if we float a cork or a toy boat on a pool over whose surface waves are passing, the cork or boat merely bobs up and down as a wave passes, but is not carried along with it.

392. Transverse and longitudinal waves. An easy way of illustrating wave motion is to fasten one end of a piece of rubber tubing about 20 feet long to a hook in the wall. If we take the free end in the hand, we can, by a quick shake, send a wave along the tube (Fig. 446). If a single depression is sent along the tube to the fixed end, it is reflected and returns as an elevation; in like manner a single elevation sent along the tube comes back as a depression.

Fig. 446. Transverse waves in a rubber tube.

In the case of water waves and of the waves in a tube or cord, the particles of water or tubing oscillate up and down,

while the disturbance moves horizontally. Such waves are called **transverse** waves.

A second kind of wave motion takes place in substances such as gases and wire springs, which are elastic and compressible. This kind of wave can be studied by letting a coil of wire represent the substance through which such waves are transmitted.

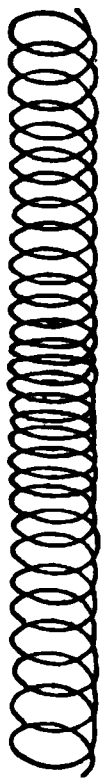


Fig. 447. Longitudinal waves in a vertical spring.

Figure 447 represents a spring whose turns are large and one of whose ends is supported from a hook in the ceiling. If we compress a few turns near the lower end, these move slightly and compress those just above; and these in turn squeeze together the turns still farther up. Thus a pulse, or wave, goes along the spring.

Next let the lower end of the spring be given a quick pull, so that the turns near by are drawn apart for an instant. Then the adjacent turns will be pulled apart, one after another, until this disturbance reaches the top. Thus it is seen that any push or pull given to the spring at one end is transmitted as a push or pull to the other end.

Waves of this sort, in which the particles of the transmitting material move back and forth in the direction of the advance of the wave, are called compression or **longitudinal** waves.

393. Longitudinal waves in solids. Not only springs, but gases and even solids like steel, transmit longitudinal waves.

If we clamp a steel rod in the middle and rub it lengthwise with a cloth dusted with rosin, a clear, ringing sound may be produced. That the rod has been set in longitudinal vibration can be shown by a little ivory ball hung by a cord so as to rest against the end of the rod. When the rod is vibrating, the ball swings out violently (Fig. 448).

A mechanical illustration of the fact that a push or pull may travel a long distance, although the individual particles move only very minute distances, is shown in figure 449.

The apparatus consists of several glass-hard steel balls hung in line so that they just touch each other. If we pull aside the first ball and let it fly back against the line of balls, the ball it strikes does not

seem to move, nor the next one. In fact, none seem to be affected by the blow except the ball on the opposite end, which flies out about as far as the first ball fell. Since steel is very elastic, the impact to the first ball is handed along from ball to ball until it reaches the end one. It is as though a push were given to the first of a column of boys standing in line. It is transmitted along the line, and the last boy is pushed over.

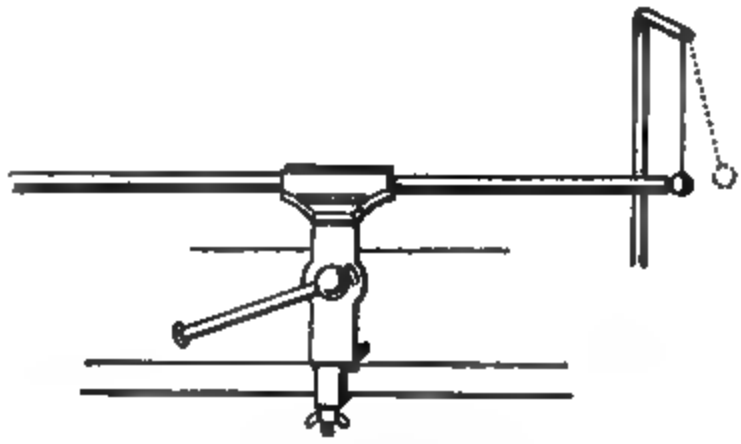


Fig. 448. Ball set in vibration by longitudinal waves in the rod

394. Sound waves. We think of the air in sound waves as vibrating to and fro in the direction of propagation like the turns of a spring; that is, *sound waves are longitudinal, or compression, waves, made up of alternate* ***condensations*** *and* ***rarefactions***. Just as a stone thrown into a pool makes waves which spread out in ever widening concentric circles, so we think of a bell as sending out **spherical** waves. These are made up of alternate spherical shells of compressed and of rarefied air, traveling out in every direction through space.

Fig. 449. Illustrating how sound travels from particle to particle.

To form a picture of a sound wave traveling through a speaking tube, let us imagine that the spiral spring of the model (Fig. 447) is replaced by a column of air, which has a tuning fork at one end, giving little pulses to the air column, while an eardrum at the other end receives these pulses (Fig. 450).

The successive condensations and rarefactions of the air are indicated by *c* and *r* in *A'B'*. The disturbance travels from the fork to the ear, but the intervening air at any point merely oscillates a very little to and fro. The curve in figure 450 is a graphical representation of these sound waves, in which the crests, 1–2, 3–4, etc., represent condensations or compressions, and the troughs, 2–3, etc., represent rarefactions. The amplitude of the wave corresponds to the distance each particle of air moves to and fro from its original position. A sound wave includes a complete crest and trough, — that is, a condensation and rarefaction, — and the distance between two corresponding points in any two adjacent waves is called the wave length.

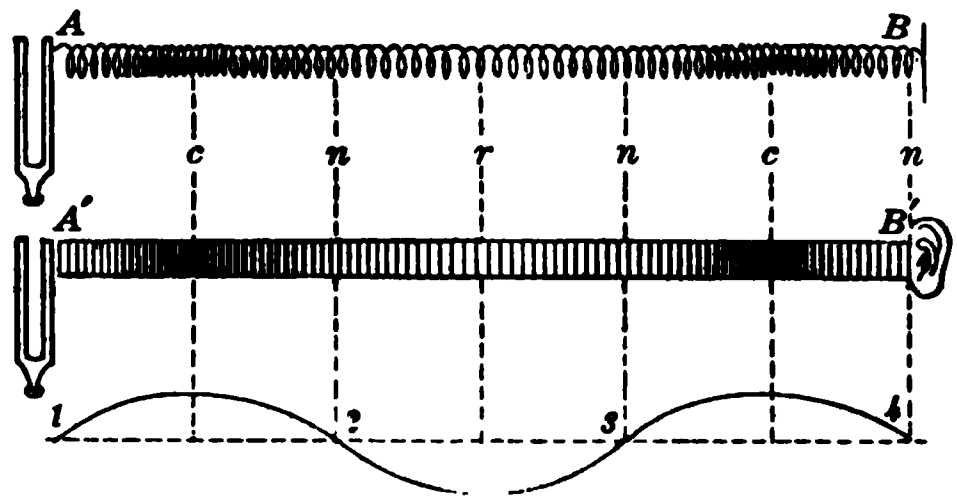


Fig. 450. Diagram to show how sound waves may be represented by a curve.

Since the same relation between velocity, wave length, and frequency holds for sound waves as for water waves, we can easily compute the length of a sound wave.

For example, suppose a tuning fork is giving 256 vibrations each second, and that the velocity of sound at 20° C. is 1127 feet per second. Then the wave length is 1127 feet divided by 256, or about 4.4 feet.

To picture a sound wave spreading through the open air, we may imagine a great number of spiral springs radiating out from a common center at the source of the sound, all receiving an impulse at the same time.

Problems

(Assume that the temperature is 0° C. unless otherwise stated.)

1. An *A* tuning fork on the international scale makes 435 vibrations per second. What is the length of the sound wave given out?

2. A vibrating string gives out sound waves 2 feet long. What is the frequency of the waves?

3. The time required for one sound wave to pass a given point is found to be 0.0025 seconds. What is the length of the wave?

4. A bell whose frequency is 150 vibrations per second is sounded under water, in which sound travels at the rate of 4800 feet per second. Find the wave length produced by the bell.

5. If the highest tone which the ear can recognize makes 30,000 vibrations per second, what is the shortest wave which the ear appreciates?

6. If a certain organ pipe at 20° C. has a pitch of 521 vibrations per second, what is the pitch (frequency) of the same pipe at 10° C.?

7. Find the vibration frequency of a violin string that sends out sound waves 1 meter long at 15° C.

8. A tuning fork makes 1024 vibrations per second, and the length of the sound wave given off is 32 centimeters. (*a*) Find the velocity of the sound. (*b*) Find the temperature on the centigrade scale.

395. Intensity, or loudness, of sound. It must always be remembered that when an electric bell is struck, the sound is heard in all directions; this means that sound waves spread out in all directions, as shown in figure 451. As the distance from the source increases, the energy in each wave spreads out over more surface, and so the intensity of the sound decreases. For example, a bell 10 feet away sounds one fourth as loud as the same bell 5 feet away, and if 15 feet away, it sounds one ninth as loud as when 5 feet away. This is because the energy of each wave must be imparted to nine times as many particles at a distance of 15 feet as at a distance of 5 feet. *In general, the intensity of sound varies inversely as the square of the distance.*

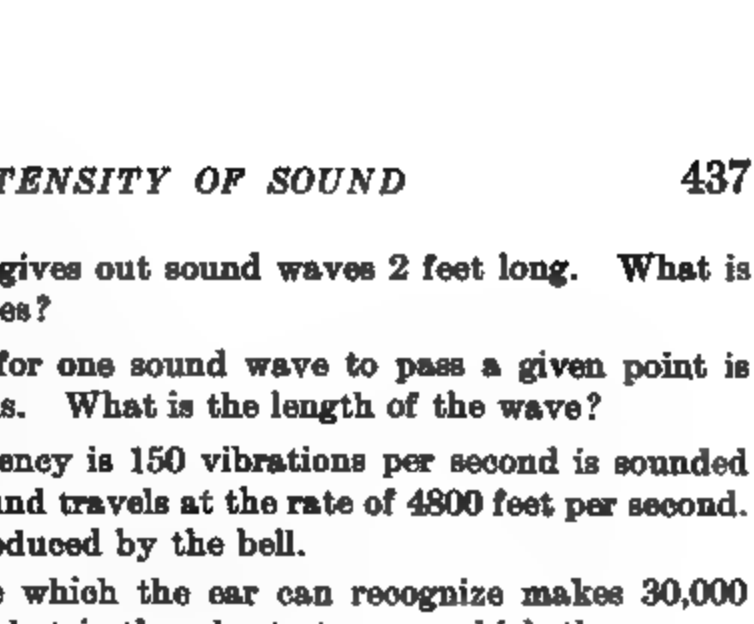


Fig. 451. Sound waves spread out in all directions from the bell

If one ascends to a high altitude, as on a mountain top or in a balloon or airplane, the air becomes less dense and hence not so good a carrier of sound. This makes it difficult to transmit sounds. *In general, the intensity of sound depends on the density of the medium through which the sound is transmitted.*

396. Speaking tubes and megaphones. The speaking tubes used to connect rooms in buildings and ships serve to prevent the spreading out of sound waves in all directions, and so the sound is heard with almost its original intensity at the distant point. Sharp bends in such tubes should be avoided, as they cause reflected waves, which dissipate some of the energy.

In the **megaphone** the sound waves which come from the mouth are not permitted by the walls of the instrument to spread out in all directions. In this way the energy of the voice is sent largely in one direction.

397. Finding the direction of sound. A listener can usually locate very accurately, even when blindfolded, the direction from which a sound comes. The only exception is that sounds which are directly in front of, above, or behind him are readily mistaken one for the other. In each of these cases, sound from the source reaches his right and his left ear at the same time, while other sounds reach one ear a little sooner than the other because of the shorter path traveled; thus it seems reasonable to suppose that it is the time interval between impingement on the nearer and on the more distant ear that gives us our sense of sound direction.

It has been found that if two equally long rubber tubes are put, one in each ear, and if the further end of one tube is scratched with a needle a few hundredths of a second sooner than the other, a blindfolded listener seems to hear only one scratch and assigns to it a perfectly definite direction on the side of the head corresponding to the earlier scratch.

These facts were made use of during the World War for locating submarines. Two little rubber bulbs on the ends of a cross arm 10 or 12 feet long under the ship served as widely separated ears. From one a tiny speaking tube led to the right ear of the observer, while

the other bulb was similarly connected to his left ear (Fig. 452). When a sound came through the water, the cross arm was rotated around a vertical axis until the sound seemed to the observer to be squarely in front of him. Then a perpendicular to the cross arm indicated the direction of the submarine within 1° or 2°.

A similar device used near the bow of an ocean liner enables a seaman to determine the direction from which the sound from the propeller at the stern seems to come after it has been reflected from the bottom of the ocean. A simple calculation, involving the length of the ship, then gives the depth, and makes soundings unnecessary when the vessel is approaching shallow water (Fig. 453).

Fig. 452. Diagram of apparatus used to detect the direction of a submarine.

Big guns were located in a similar way during the war; except that little electrical "ears" were put out half a mile apart behind the battle front, and the interval between the arrival of the boom of the gun at one "ear" and at another was recorded by sensitive galvanometers on a moving film. This was called **sound-ranging**.

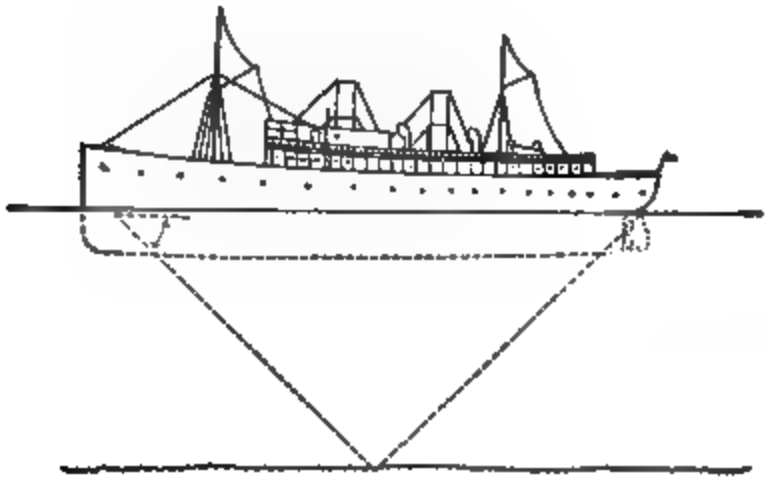


Fig. 453. A method of finding depth of water by determining the direction of sound from ship's propellers.

398. Reflection of sound. Just as any elastic body, like a rubber ball, bounds back when thrown against a brick wall, or a water wave is turned back by a stone embankment, so a sound wave is turned back, or **reflected**, when it strikes against another body, such as a building, cliff, or wooded hillside, or even a cloud. The returning wave is called an **echo**. The reflecting surface has to be 20 or 25 yards distant, for the echo

to be distinct from the original sound. The greater the distance, the longer is the time before the reflected wave strikes the ear, and therefore the more striking the echo becomes. When we have parallel walls, as in a narrow cañon, or objects at different distances, the echo is multiple or repeated, which means that the same sound is heard several times. For example, the roll of thunder results in part from the reflection of the sound from a succession of mountains or clouds.

The following experiment shows that sound waves, like light waves, are reflected by curved surfaces. If two large parabolic mirrors face each other, as shown in figure 454, a watch at the principal focus of one mirror can be distinctly heard across the room by holding an ear trumpet at the focus of the other mirror.

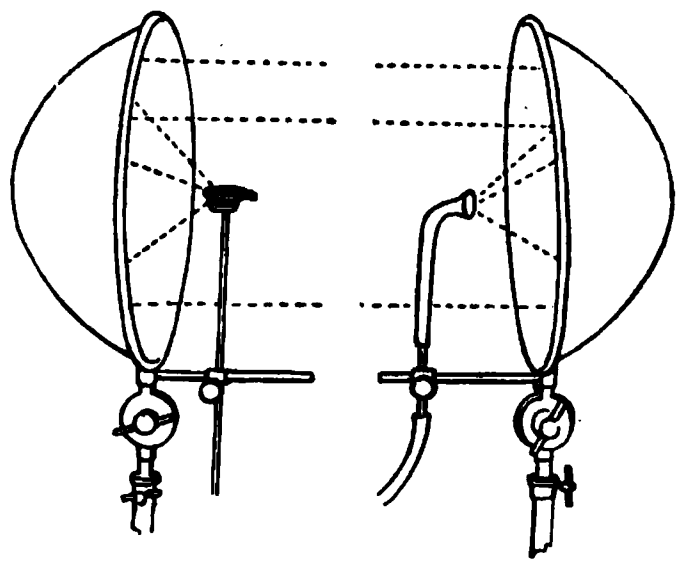


Fig. 454. Ticking of a watch reflected by mirrors.

In buildings with arched ceilings such as the dome at the Capitol at Washington it is possible to hear a whisper at a very distant place in the room, because the sound is reflected from the ceiling and concentrated at the ear of the listener.

399. Sound in rooms. Some halls and auditoriums are very unsatisfactory because it is almost impossible to hear well in them. It is therefore important to be able both to correct acoustical defects in existing auditoriums and to avoid them in designing new ones.

Sometimes hearing is easy for those in some parts of a room and hard for those in other parts. This sort of trouble is usually due to one or more **reflections** of the speaker's voice from particular parts of the walls or ceiling, which produce, either echoes following so closely after the direct sound as to confuse hearers, or "dead spots," where a reflected wave "interferes" (section 414) with the direct wave. Such cases are studied by actually photographing waves of sound as they pass through a small cross-sectional model of the

auditorium in question (Fig. 455). The remedy for a bad case is to put sound-absorbing material, such as heavy tapestries or hair felt, on the surfaces from which the objectionable reflections come.

Another kind of trouble is due to what is known as **reverberation.** When a steady musical note or vowel tone is sounded in a room, the sound waves pouring out are irregularly reflected back and forth from the walls, floor, and ceiling until the whole room is uniformly filled with sound. This sound is continually dying out, because each reflection of each wave is accompanied by more or less absorption of the sound energy. Thus an open window acts as if it absorbed all of the sound that reaches it, because it lets all through and reflects none.

Fig. 455. Vertical cross section of a model of a theater, showing a sound wave moving toward the left.

In the meantime, fresh energy is being poured into the room from the source of the sound, and the general loudness very quickly increases to a point where all the absorption just equals the flow from the source. If now the source is suddenly stopped, the sound already in the room begins to die away, but remains audible for an appreciable time, sometimes three or four seconds. The duration of audibility after the source has stopped is used as a measure of the reverberation of the room. If the reverberation is too small, a room seems dead and uninspiring. If, on the other hand, the reverberation is too great, three or four of the speaker's words may still be ringing in our ears while a fifth is being spoken, and there is confusion and unintelligibility. Most cathedrals and many stone churches have this fault, and it has led to the custom of intoning the service, that is, singing it all on one note, so that all the words that are being heard at any one instant may sound well together.

Careful experiments by Sabine at Harvard University a few years ago showed that a room must have a reverberation of almost exactly one second to be good for orchestral music. He also showed, not only how to correct excessive reverberation by putting felt on the walls or ceiling, or by using sound-absorbing furniture, hangings, statuary, or plants, but also how to design new auditoriums so that they shall have just the right reverberation, by choosing proper materials for the walls and ceiling. He even made acoustically good stone churches possible by finding a special kind of artificial stone or tile that absorbs many times as much sound as ordinary stone.

400. Musical sounds and noises. We all recognize some sounds, such as the slamming of a door or the rumbling of a wagon over cobblestones, as **noises**; while we recognize the sounds from a piano wire or an organ pipe as **musical sounds** or **tones**. The difference between these kinds of sounds can be best expressed by the curves in figure 456, where *A* is the curve of a noise and *B* the curve of a musical note.

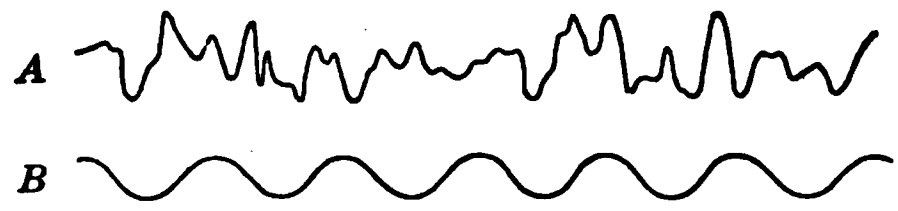


Fig. 456. Curves to represent (A) noise and (B) music.

It will be seen from these curves that a noise makes a very irregular and haphazard curve, while a musical note makes a uniform and regular curve. The latter produces an agreeable sensation on the ear, while the former makes a disagreeable sensation.

401. Three characteristics of a musical tone. A musical sound or tone has intensity or loudness, pitch, and quality or timbre; and each of these characteristics depends upon some physical property of the sound wave. The **intensity** depends on the amplitude of the vibration, the **pitch** on the frequency of the waves, and the **quality** on the vibration form.

402. Intensity. We have already seen that in general the intensity of sound diminishes as the distance of the ear from the source of the sound increases, and also as the density of the air diminishes. The **intensity** of a musical sound for a given

ear and at a given distance depends on the amplitude of vibration of the waves. Thus, a piano string or a tuning fork gives a louder sound when struck hard than when struck gently.

403. Pitch. When we speak of a musical note as high or low, we refer to its pitch. When we strike the keys of a piano in succession, beginning at one end of the keyboard, we recognize the difference in the tones produced as a difference in pitch. By holding a card against the teeth of a rapidly revolving wheel, we can show that the pitch of the note produced depends on the number of vibrations per second; that is, upon the frequency of the vibrations

We can show this very clearly by means of a **siren**. This is a metal disk (Fig. 457) with holes equally spaced around the edge, which can be rotated by some sort of whirling apparatus. If a current of air is directed through a tube against the outer row of holes, the regular succession of puffs produces a musical tone. As we increase the velocity of the wheel, the tone becomes higher; that is, its pitch is raised.

When we place the nozzle of the air current opposite the row with half the number of holes, we find that the note is lower, and when we place the nozzle opposite the row of irregularly spaced holes, we have a noise.

Fig. 457. The pitch varies with the speed.

One way to measure the frequency of vibration of a musical tone is by means of such a rotating disk. Suppose the disk has 48 holes, and is attached to a motor making 1800 revolutions per minute. Since the disk makes 30 revolutions per second, there are $30 \times 48 = 1440$ puffs per second. The frequency of the tone emitted would be 1440 vibrations per second. This would be a rather shrill note. A standard *A* tuning fork makes only 435 vibrations per second.

404. Limits of audibility. The lowest tone which the human ear can recognize as a musical tone has a frequency of about 16 vibrations per second. If the sound has a frequency above a certain number, the ear does not hear it at all. This upper limit of audibility varies with different people from

20,000 to 40,000 vibrations per second. One of the evidences of the impairment of hearing with advancing age is the increasing inability to hear sounds of high pitch.

405. Quality, or timbre. The third characteristic of a musical note is its **quality**. It is quality which enables us to distinguish between notes of the same pitch and intensity when produced by different instruments or sung by different voices. Even the same kind of instrument may produce notes of different quality. For example, it is the quality of the tones produced by two violins which makes the great difference in their value. We recognize the voice of a friend over the telephone by its quality.

Helmholtz (Fig. 458) first discovered the cause of these subtle differences in musical tones which are called quality. In this investigation he made use of resonators which vibrated in sympathy with the tones to be studied.

Fig. 458. Hermann von Helmholtz (1821–1894). German physiologist made important discoveries in mechanics, sound, and light.

406. Sympathetic vibrations. Everyone has learned by experience how easy it is to set a swing vibrating by a succession of gentle pushes applied at just the right time, so that each push helps rather than hinders the swinging. Mere random pushes, on the other hand, accomplish very little. In much the same way, sound waves or other slight impulses may set up strong vibrations in a body if they are timed to correspond exactly to its natural frequency of vibration. This is called **sympathetic vibration.**

This can be strikingly shown by holding down the loud pedal of a piano, so that the dampers are lifted from the strings, and singing a clear, strong tone into the instrument. After the voice is silent, the sound is returned by the strings with startling fidelity.

Another way to illustrate sympathetic vibrations is to put two mounted tuning forks of the same pitch several feet apart (Fig. 459). If we strike one fork vigorously with a soft mallet, and then quickly stop it with the hand, the other will be heard even in a large room. It has been set in motion by the sound waves from the first fork. If we change the pitch of one fork by placing a slider on one prong, the forks will be thrown slightly out of unison and will no longer respond to each other.

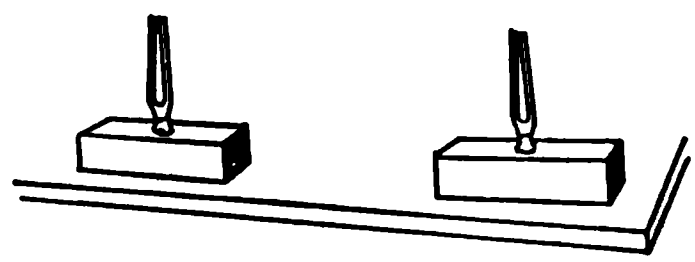


Fig. 459. Sympathetic vibration of forks of the same pitch.

From this experiment it is evident that two tuning forks must vibrate at exactly the same rate to vibrate in sympathy. Certain articles of furniture and of glassware have definite rates of vibration of their own, and are set vibrating sympathetically when their particular note is sounded. It is the cumulative effect of feeble impulses repeated many times at regular intervals which sets up this sympathetic vibration.

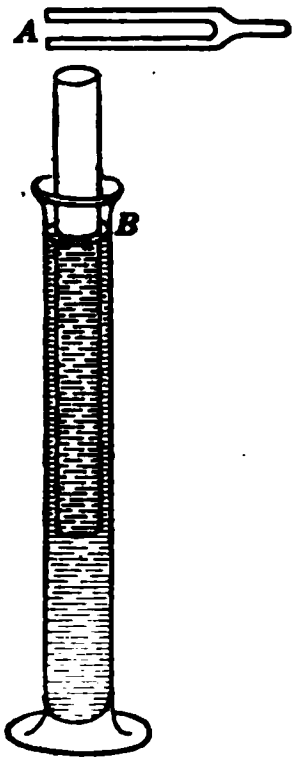


Fig. 460. Reënforcement of a sound by an air column.

407. Resonators. The sound waves started by a vibrating body will cause another body near it to vibrate, provided the two have the same rate of vibration. Such bodies are in **resonance.** In the last experiment each tuning fork stood on a wooden box open at one end and so constructed that the air column within the box had the same rate of vibration as the fork itself. Such an air column is called a **resonator.** It was the resonator rather than the fork itself that picked up the vibrations.

To show resonance, we may raise and lower the tube *A* (Fig. 460) in the jar of water *B*, and at the same time hold a vibrating tuning fork over the tube. We shall find a position where the sound of

the fork is reënforced by the sound of the air column and seems loudest.

This reënforcement or intensification of sound by a resonator is due to the unison of direct and reflected waves. For example, it can be shown that the length of air column used in the experiment is one quarter of a wave length. This will be readily understood from the diagram (Fig. 461), where *ac* is one prong of a fork vibrating over an air column in resonance. When the prong moves *down* past its central position, it causes a condensation in the column of air, which goes to the bottom and gets back just as the fork is moving *up* past its central position. This reënforces the vibration of the fork. Since the sound traveled twice the length of the air column in the time of half a vibration of the fork, it traveled the length of the air column in the time of a quarter vibration. So the vibrating air column is a quarter of a wave length. Further experiments would show that a resonance column may be 3, 5, 7, or any odd number of quarter wave lengths.

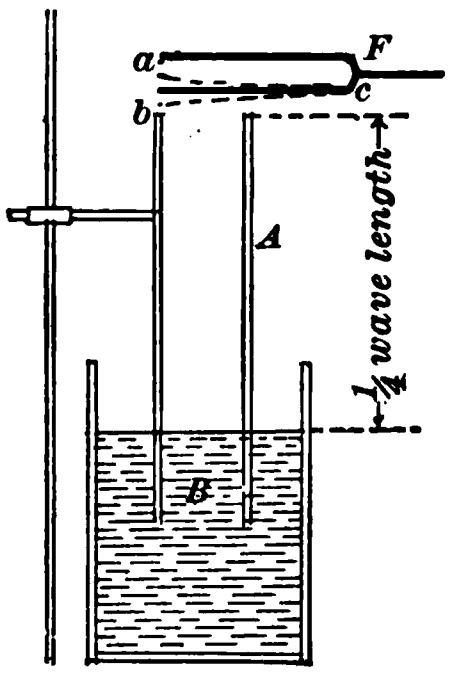


Fig. 461. The cause of resonance.

408. Forced vibrations. When a tuning fork is struck, we must hold it close to the ear to hear the sound; but if we place its base firmly against the table top, the sound is greatly intensified. If we repeat the experiment with another fork of a different pitch, we find its sound is also reënforced. Evidently the table intensifies the sound of any fork, while an air column would intensify only a single note.

The vibrations of the fork are carried through its base to the table top and force the latter to vibrate with the same frequency. The large surface of the table top sets a large quantity of air in vibration and so sends a wave of great intensity to the ear. Sounding boards in pianos and other stringed instruments act in much the same way as the table top in this experiment. Such vibrations are called **forced** because they can be produced by fork or string, no matter what its pitch.

409. Fundamentals and overtones. When a piano wire vibrates as a whole, it gives out what is called its **fundamental** note. This fundamental is the lowest note which it can give out. Its pitch depends on the length, tension, size, and material of the wire. When a wire is vibrating as a whole, it may at the same time be vibrating in segments; that is, as if it were divided in the middle. Such a secondary vibration gives an **overtone** which has twice the frequency of the fundamental and is an octave higher. It is called the *first* overtone. In a similar way, a string may vibrate as a whole and, at the same time, as if divided into thirds; in this case it gives its fundamental and its *second* overtone (Fig. 462). Higher overtones, or " harmonics," are also possible.

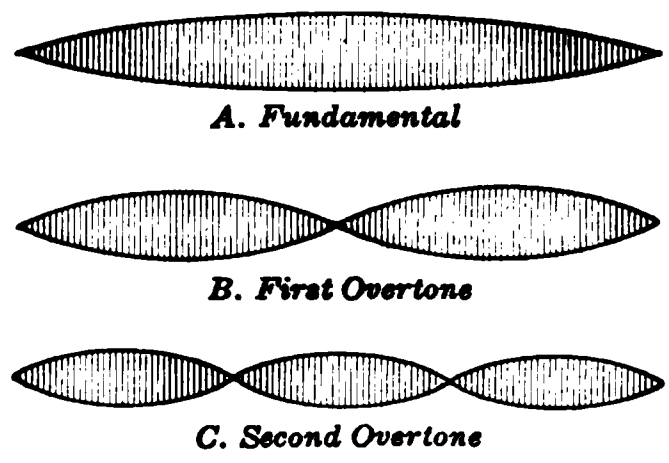


Fig. 462. A wire emitting its fundamental and its first and second overtones.

410. Helmholtz's experiment. Helmholtz proved that *the quality of a tone is determined simply by the number and prominence of the overtones which are blended with the fundamental.* To prove this, he constructed a large number of spherical resonators (Fig. 463), each having a large opening A, and also a small one B adapted to the ear. A resonator of this form is especially useful because it responds easily to vibrations of *one pitch only* and so can be used to analyze sounds. By holding each of these resonators in succession to his ear, he was able to pick out the constituents of any musical note which was being sounded, and to judge of their relative intensities. Then he reversed the process and combined these constituent overtones, reproducing the original tone. He thus succeeded in imitating the qualities of different musical instruments, and even of various vowels.

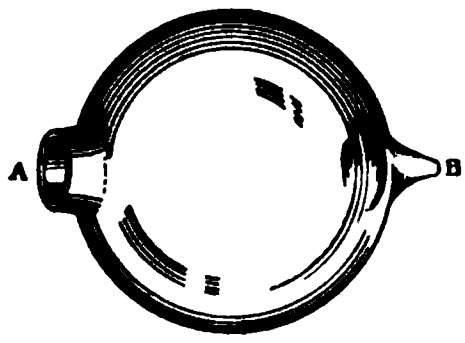


Fig. 463. Helmholtz's resonator.

411. Koenig's manometric flames. Another method of showing that the quality of any note depends on the *form of the wave* was devised by a Frenchman, Koenig. This method, called **manometric flames**, has the advantage of making the phenomenon visible.

The apparatus is shown in figure 464. The essential part is a small box divided into two chambers by an elastic diaphragm, made of very thin sheet rubber or goldbeater's skin. The cavity on one side is

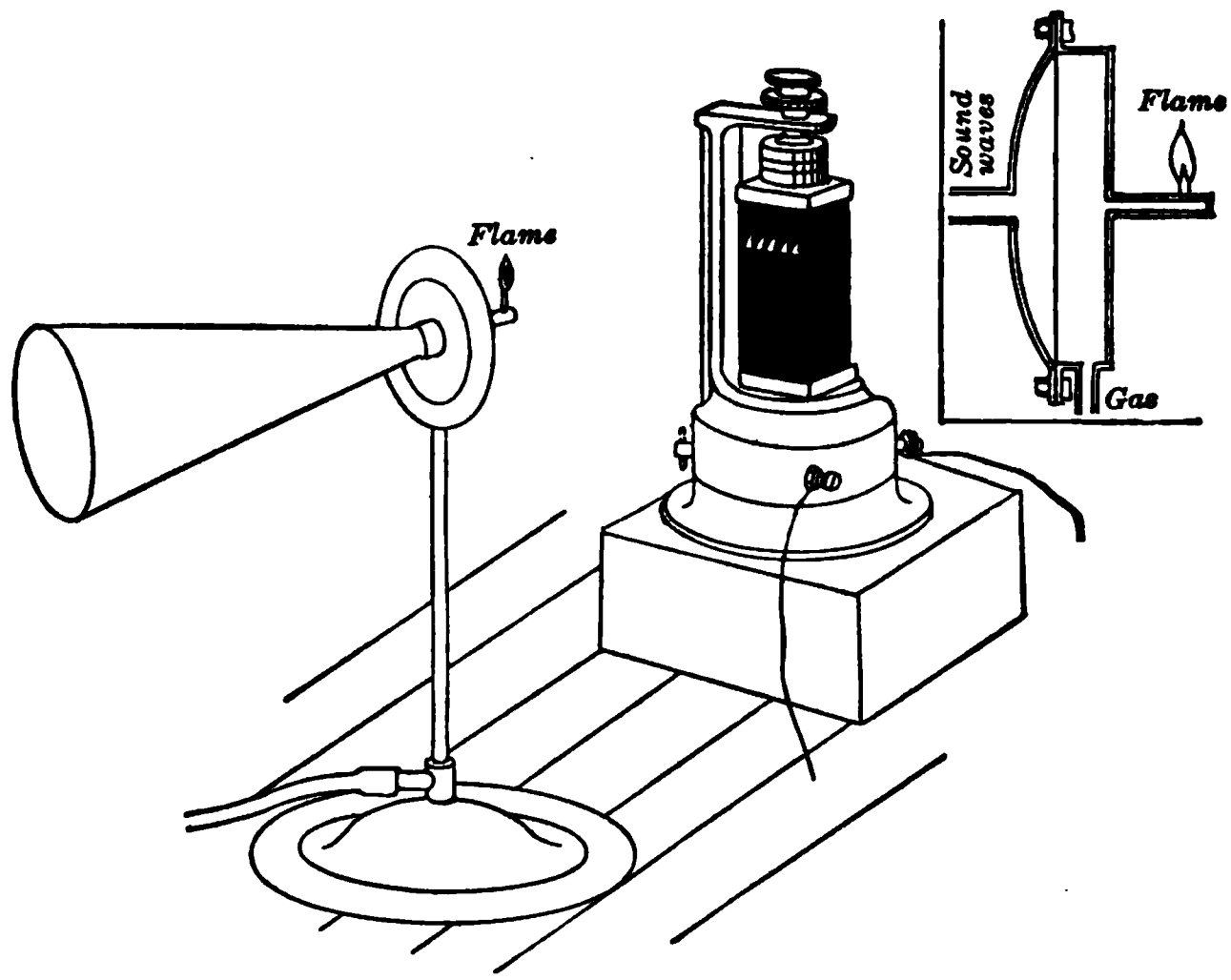


Fig. 464. Analysis of sounds with manometric flames.

connected with a funnel, while the cavity on the other side has two openings, one for illuminating gas to enter, and the other connected with a fine jet where the gas burns in a small flame. The vibrations of the air on one side of the diaphragm change the pressure of the gas on the other side, and cause the flame to dance up and down.

Let us set up the apparatus and rotate the mirror when no note is sounded before the funnel. There will be no fluctuations in the flame (Fig. 465 *a*). Next let an organ pipe be sounded in front of the mouthpiece. Then let each of the vowels be spoken into the funnel with the

same pitch and loudness. The ribbon of flame seen in the mirror is different in each case (Fig. 465 *b*, *c*, and *d*).

Manometric flames can be used to study sound vibrations of such high frequency that they are quite inaudible.

412. Photographing sound waves. Professor Dayton C. Miller has invented a very sensitive instrument which photographically records sound waves and which, in a modified form, can be used to project such waves on a screen. This little instrument, named the "phonodeik," is very simple in design but extremely delicate in construction.

Fig. 465. Forms shown by manometric flames.

The principle is shown in figure 466: *h* is the receiving tube; *d*, a diaphragm of thin glass; behind the diaphragm is a minute steel spindle mounted in jeweled bearings, to which is attached a tiny mirror *m*; one part of the spindle is a small pulley; a few silk fibers are attached to the center of the diaphragm and, after being wrapped once around the pulley, are fastened to a spiral spring; a ray of light from the pinhole *l* is focused by a lens and reflected by the mirror to the moving film *f*. As the sound wave causes the diaphragm to move back and forth, the mirror is rotated and the spot of light traces a record of the sound wave on the film as in figure 467.

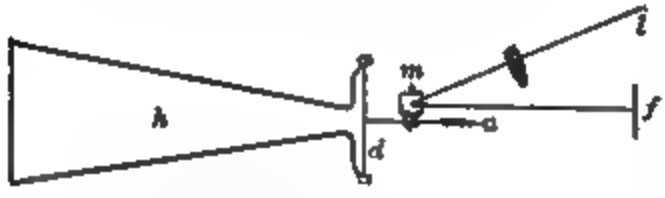


Fig. 466. Diagram of the phonodeik, used to photograph sound waves.

PROBLEMS

(Assume that the temperature is 0° C. unless otherwise stated.)

1. If two men are 1000 feet and 2500 feet from a foghorn, how many times as loud does the horn sound to one man as to the other?

Fig. 467. Photograph of the words "Bureau of Standards" spoken by Professor Dayton C. Miller of the Case School of Applied Science, Cleveland, Ohio. Record made by the phonodeik. Dots indicate time intervals of 0.01 seconds.

2. Six seconds elapse between the firing of a gun and its echo from a cliff. If the temperature is 15° C., how far away is the cliff?

3. A tuning fork is reënforced when held over an air column 6.5 inches long. What is the wave length?

4. A tuning fork whose normal frequency is 435 is mounted on a wooden box, which acts as a resonator. If we neglect the correction for the end, how long must the box be?

5. A whistle has a resonating column of air 1.5 inches long. Find the vibration frequency of its tone.

6. The parallel walls of a cañon are vertical and 5000 feet apart. A man fires a gun in the cañon and hears two echoes, the second 3 seconds after the first. How far is he from the nearer wall? Assume the velocity of sound to be 1100 feet per second.

7. A tuning fork is reënforced when held over an air column 10 centimeters long, and the next position of resonance occurs when the air column is 25 centimeters long. Assuming the velocity of sound to be 345 meters per second at the temperature of the room, compute the frequency of the fork.

8. Find the frequency of a tuning fork which produces resonance in a column of air 50 centimeters long at 15° C.

413. Interference of sounds. We have seen in studying resonators that two sound waves may unite so as to reënforce each other. It is also possible to make two sound waves unite so as to interfere with or destroy each other. That is, *under certain conditions the union of two sounds can produce silence.* This is the cause of the phenomenon called **beats.**

If we place two mounted tuning forks of the same pitch side by side, and strike the forks in succession with a soft mallet, we hear a smooth, even tone. But if we change the pitch of one fork by attaching a slider to one prong, and repeat the experiment, we hear a throbbing, or pulsating, sound. The throbs are called beats. They are due to the alternate interference and reënforcement of the sound.

If two adjoining notes of a piano or organ are struck at the same time, beats are heard, especially if the notes are in the lower part of the scale.

Beats are used to tune two strings or forks to the same pitch. The forks are adjusted until no beats are heard.

414. Explanation of beats. To show how two sound waves can combine to produce no sound, let *A* in figure 468 represent a sound wave, and *B* another wave of exactly the same period, but *opposite in phase;* that is, just a half wave length behind the first. If the two impulses which would generate two such waves were applied to the air, it would not suffer any disturbance at all (curve *C*). This is **interference** of sound waves.

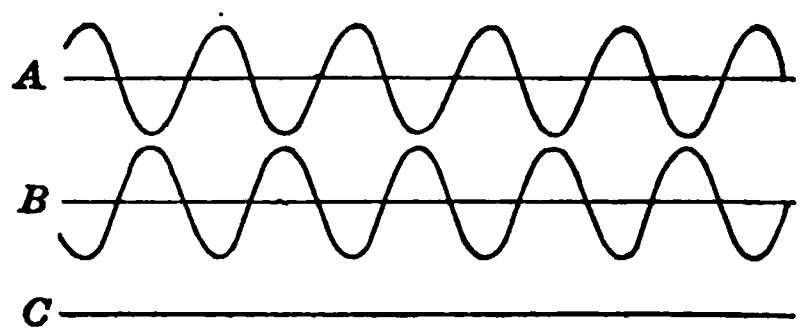


Fig. 468. Two waves of same period but opposite phase.

If two waves of the same period are *in phase*, or in step, as *A* and *B* in figure 469, they reënforce each other and produce a sound of double amplitude, as shown by the bottom curve *C*. This is **reënforcement** of sound waves.

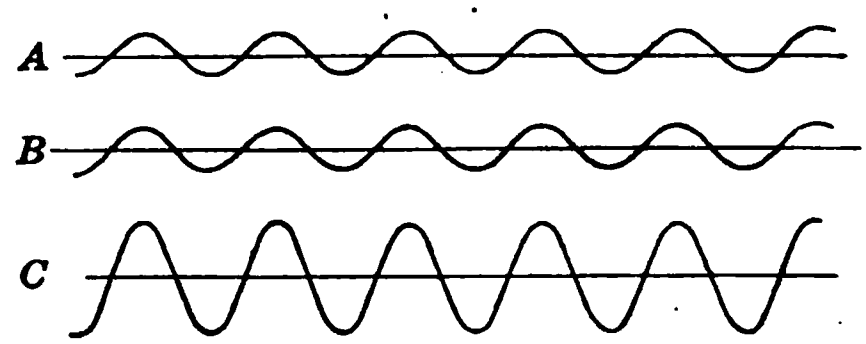


Fig. 469. Two waves in step produce reënforcement.

Finally, if two waves of slightly different period (*A* and *B*, in figure 470) are superposed, there will be reënforcement at some points and interference at other points (curve *C*).

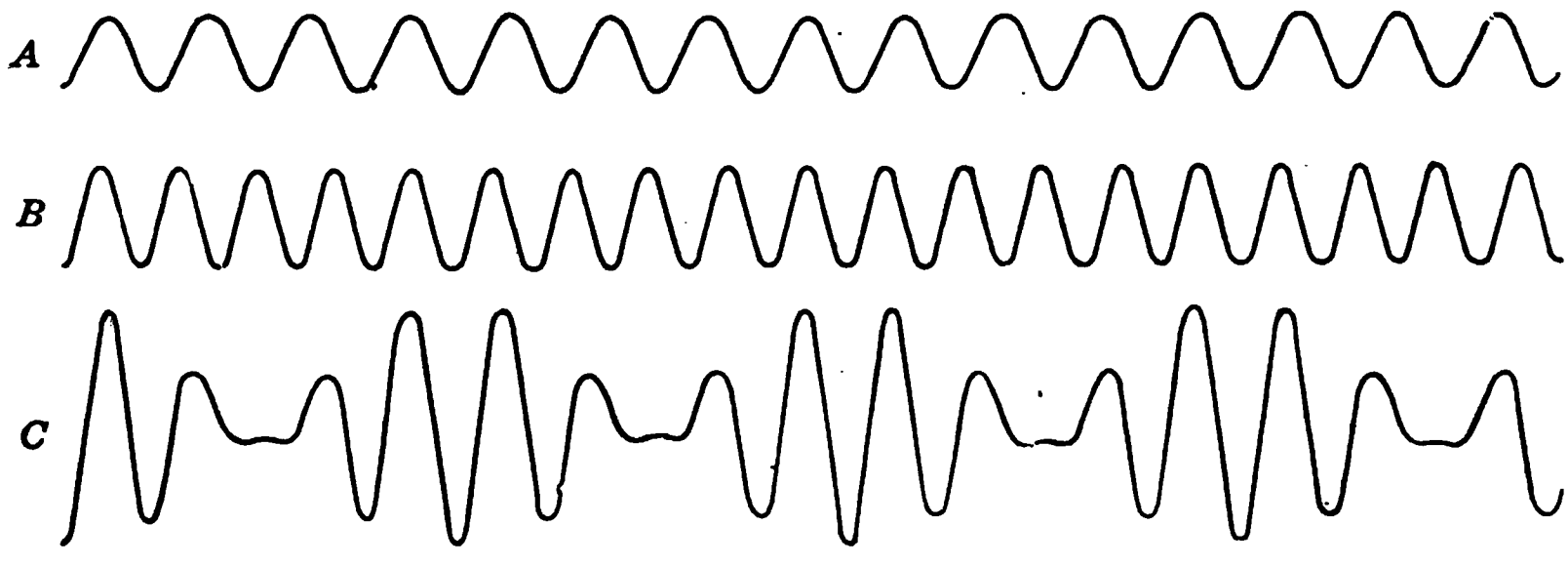


Fig. 470. Curves to show how beats are produced.

Evidently, if the waves make respectively 255 and 256 vibrations per second, there will be one reënforcement and one interference (that is, one beat) each second. In general, *the number of beats per second is equal to the difference between the frequencies of the waves.*

415. Discord and beats. Experiments show that discord is simply a matter of beats. If there are six or more beats per second, the result is unpleasant; if there are about thirty, there is the worst possible discord. But when the vibration numbers differ by as much as seventy, as do the notes *C* and *E*, the effect is harmonious. If two musical tones with strong overtones are to be harmonious, it is essential that there shall not be an unpleasant number of beats between any of their overtones. This is the reason why the bells of chimes are struck in succession, not simultaneously.

416. The musical scale. So far we have been studying the behavior of a single train of waves in the air, and the propagation of a single musical tone; now we shall consider some of the fundamental **relations** between musical tones. That is, we shall seek a scientific basis of music.

When we wish to compare two musical tones, we first consider their pitches or frequencies. Notes of the same frequency are said to be in **unison.** When two notes have frequencies as 1 to 2, the relation, or interval, is called an **octave.** Thus, a note whose frequency is 512 is one octave *higher* than another whose frequency is 256; and one whose frequency is 128 is an octave *below* the note whose frequency is 256.

It has been found that the ear recognizes as harmonious only those pairs of notes whose frequencies are proportional to any two of the simple numbers, 1, 2, 3, 4, 5, and 6. It is still more remarkable that the ear of man has for centuries recognized that *three* notes are harmonious when their frequencies are as 4 : 5 : 6. This combination is called the **major triad.** Any combination or rapid succession of tones not characterized by simple frequency ratios produces a discord.

The **major scale** is a sequence of tones so related that the 1st, 3d, and 5th form a major triad; also the 4th, 6th, and 8th (or octave of the 1st); and also the 5th, 7th, and 9th (or octave of the 2d). This is shown in the following table, where the tones of the scale are represented by the letters used in musical notation.

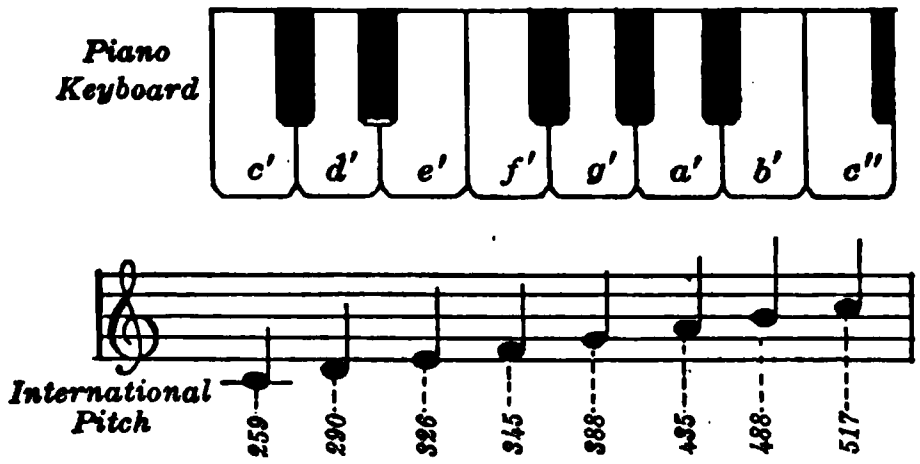


Fig. 471. Notes of an octave on a piano keyboard.

The arrangement of the notes of an octave on the keyboard of a piano is shown in figure 471. The white keys correspond to the notes of an octave, the black keys to intermediate notes, used in forming other scales.

TABLE OF RELATIONS BETWEEN NOTES OF AN OCTAVE

C (do)	D (re)	E (mi)	F (fa)	G (sol)	A (la)	B (si)	c (do)	d (re)
4		5		6			(8)	
			4		5		6	
	(3)			4		5		6
1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2	$\frac{9}{4}$

Any frequency, or vibration number, may be chosen for the first note C of the octave and the series built up as indicated. In fact, several such pitches have been in common use as the starting point. The so-called **international pitch** takes 435 vibrations for middle A (the second space on the treble clef), and this makes middle C (the lower C on the treble clef) 258.6. In physical laboratories C forks usually have a frequency of 256, to make the arithmetic easier.

Musical Instruments

417. Piano. We are all familiar with the **piano**, or at least we have seen its keyboard, which usually has 88 keys. When we open the case, we find 88 wires of various lengths and sizes. Each key operates a felt hammer, which strikes a wire and thus produces a note of definite pitch. We may also notice that the notes of lower pitch are produced by long, large wires and the notes of higher pitch by short, thin wires. Perhaps we have watched a piano tuner loosen or tighten a wire by turning with a wrench a pin at one end.

If we stretch a piece of steel wire along the table and set it vibrating, we find its tone is very weak compared with the tone of a piano. This is because the piano has a sounding board directly beneath the wires. The vibrations of the wires are transmitted through the frame to this large, thin board, causing it to vibrate also. The board then sets in vibration a larger quantity of air than the string alone could affect, and produces a louder tone.

418. Laws of vibrating strings. We may show by means of a sonometer (Fig. 472), which is simply a metal wire stretched across a

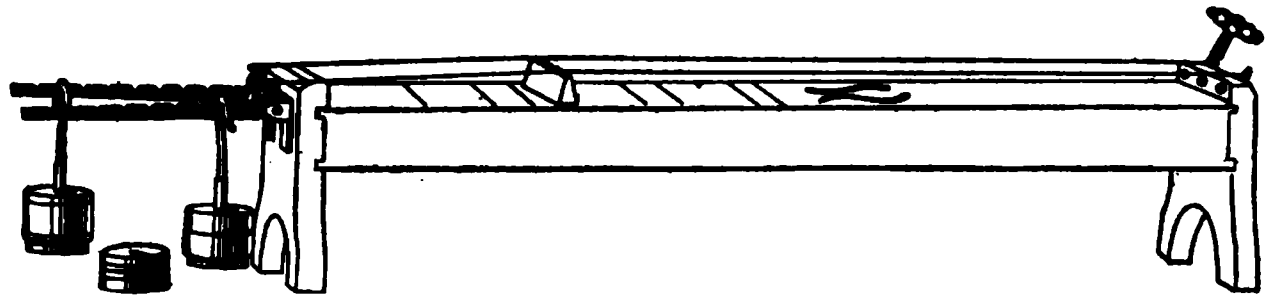


Fig. 472. A sonometer used to illustrate the laws of vibrating strings.

long wooden box, that the pitch, or frequency, of a wire is raised by tightening the wire. If the pull on one wire is exactly four times as great as that exerted on the other wire, then the note of the first wire will be found to be an octave above that of the second wire. If we introduce a movable bridge or fret, the pitch is raised. The shorter we make the wire, the higher is the pitch. Finally, we may show that a *larger* wire of the same length and under the same tension gives a lower note.

Careful experiments of this sort have proved the following laws:

(1) *The vibration frequency varies inversely as the length of the vibrating string.* Thus the pitch of a wire under constant tension is raised an octave by putting the movable bridge in the middle.

(2) *The vibration frequency varies directly as the square root of the tension.* Thus, if a pull of 4 pounds on a string gives 100 vibrations per second, a pull of 16 pounds is required to raise the pitch an octave, or to give 200 vibrations per second.

(3) *The vibration frequency, or pitch, varies inversely as the square root of the weight per unit length of the string.* This is why the wires of a piano which give the low notes are wound with wire to get the necessary weight.

419. Other stringed instruments. The **violin, mandolin, and guitar** have sets of strings tuned to give certain notes, and wooden bodies to reënforce the tones of the strings. These instruments differ from the piano in that they have but few strings, and in that their strings are set in vibration by bowing or picking instead of by striking them with a hammer. Each string is made to give a large number of notes by pressing on it at various places and so changing its length. The particular place and manner in which the string is plucked or bowed determines the overtones and thus the quality of the tone. In this way the violin may be made to give tones with a wide range not only of pitch but also of quality.

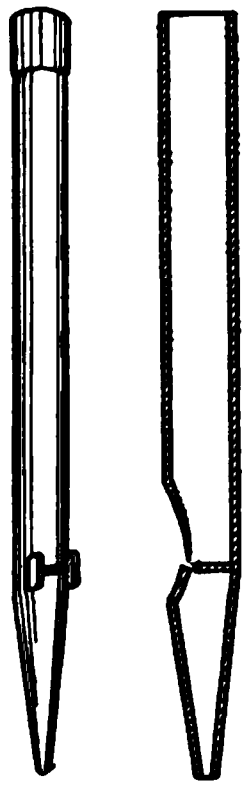


Fig. 473. Organ pipe, outside view and cross section.

420. Wind instruments. The simplest wind instrument is the **organ pipe.** Sometimes the tube is open at the upper end and is called an *open* pipe (Fig. 473); at other times the pipe is closed at the upper end and is called a *closed* pipe.

If we blow an open pipe, the current of air strikes against a sharp edge and is set in vibration. The tube acts as a resonator. The lowest note which such a pipe gives out is the one whose wave length is twice the length of the pipe. This note is called its fundamental. If we close the end of the tube with the hand, thus making a closed pipe, we shall find that the lowest note is an octave lower, or one whose wave length is four times the length of the pipe. This is called the fundamental note of the closed pipe.

In general, then, *the length of an open pipe is one half the wave length of its fundamental, and the length of a closed pipe is one quarter of the wave length of its fundamental.*

It will be noticed that the resonance tube in the experiment in section 407 is a closed pipe upside down, the tuning-fork end corresponding to the lip end of an organ pipe.

The **flute**, **clarinet**, **cornet**, and **trombone** are also wind instruments. In the first two, the column of air is broken up by means of holes. The opening of a hole in the tube is equivalent to cutting the tube off at the hole. The length of the air column within the cornet and certain other instruments can be changed by fixed amounts by means of pistons *a*, *b*, and *c*,

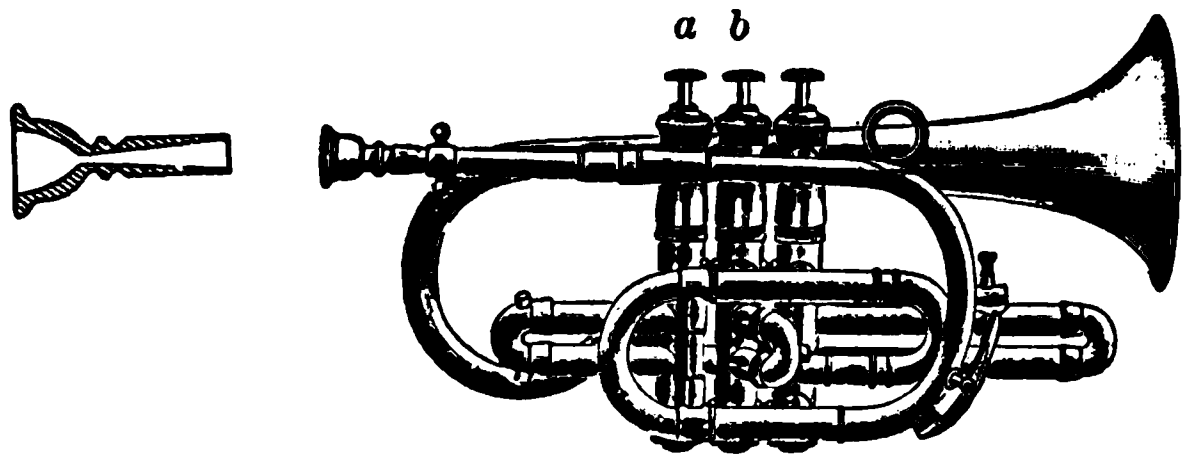


Fig. 474. The cornet and its mouthpiece.

shown in figure 474. In the trombone the length of the air column can be varied by sliding a portion of the tube in and out. It is also possible to vary the notes by blowing harder and so getting overtones.

In wind instruments of the **bugle** or **cornet** type, the vibration of the air is caused by the vibrating lips of the musician.

421. Vibrating membranes. One example of this sort of musical instrument is the **drum.** Another is the most wonderful musical instrument of all, the **human voice.** Its notes are produced by the vibration of a pair of membranes, one on each side of the throat, called the vocal cords, and also by the vibration of the tongue and lips. By changing the muscular tension on the vocal cords, one changes the pitch of the voice; and by changing the shape of the mouth, one changes the overtones, and so the quality of tone.

PROBLEMS

(Assume that the temperature is 0° C., unless otherwise stated.)

1. An open pipe is 4 feet long. What wave length does it give?

2. What is the length of an open pipe which gives a tone an octave above that in problem 1?

3. A siren has 50 holes. How many revolutions per minute will it have to make to produce a tone whose frequency is 435?

4. A fork making 256 vibrations per second is reënforced by a tube of hydrogen 4 feet long. Find the velocity of sound in hydrogen.

5. Find the number of vibrations of a note three octaves below a note whose frequency is 264.

6. What is the fourth overtone of a string whose fundamental tone has a frequency of 256?

7. A certain stretched piano wire vibrates 400 times a second. What will be the frequency of another wire of the same material which is one half the diameter of the first wire, and is stretched between supports one half as far apart as the first, and with one half the tension?

8. How long would an open organ pipe need to be to give as its fundamental tone the note middle A (international pitch)?

9. How many centimeters long would the closed pipe of a whistle need to be to give middle C (international pitch)?

10. How many beats per second will be produced by sounding together two open organ pipes 20 inches and 21 inches long respectively, when the temperature is 20° C.?

422. The phonograph. The phonograph (Fig. 475) is a remarkable machine for reproducing sound. When one

speaks into the mouthpiece, the waves set a diaphragm vibrating; this makes a fine metal or sapphire point, which can move up and down, cut a spiral groove of varying depth in a wax cylinder. The bottom of this groove is a wavy line

Fig. 475. Cylinder form of phonograph and diaphragm with recording and reproducing points.

representing the condensations and rarefactions of the sound waves.

To reproduce the sound, a small round-ended needle is attached to the diaphragm and follows the groove in the wax

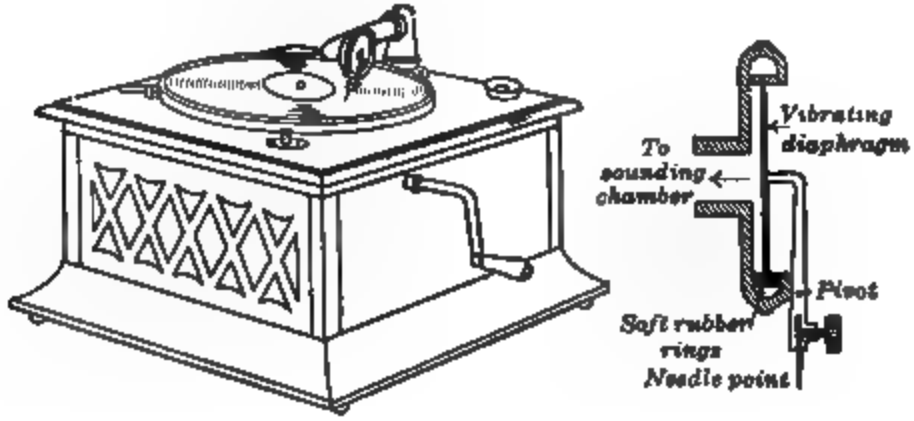


Fig. 476. Disk form of phonograph with diagram of diaphragm and needle.

as the cylinder turns. The varying depth of the groove moves the needle up and down and thus makes the diaphragm vibrate in such a way as to reproduce the original sounds. In

the machine shown in figure 475, the sharp and the round-ended points are both mounted near the center of the same diaphragm, as shown at the right. The diaphragm can be moved forward and back a little so that only one of these points touches the cylinder at any time.

In another style of phonograph (Fig. 476), the wax is made in the form of a disk instead of a cylinder, the needle point vibrates from side to side instead of up and down, and the diaphragm is vertical. In still another type, a disk is used, but the diaphragm is horizontal and is vibrated by the up-and down motion of a diamond point (Fig. 477).

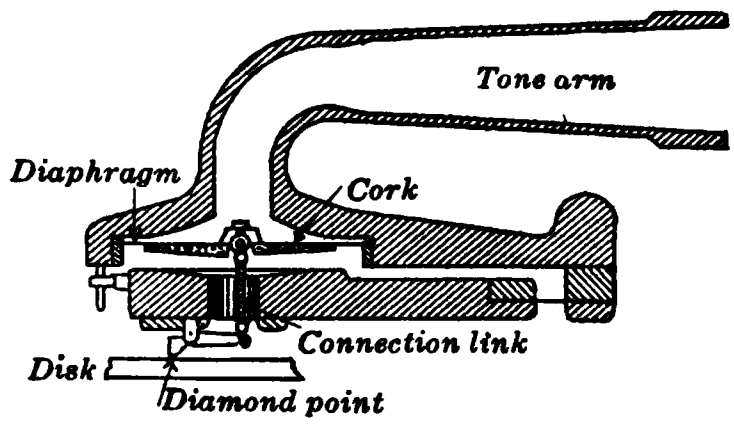


Fig. 477. Section of Edison diamond reproducer.

A phonograph does not reproduce the consonant sounds very distinctly, words being chiefly recognized by the vowel sounds, which come out strong and clear. This is because the vowel sounds are more or less clearly defined musical tones, and produce regular vibrations; but the consonant sounds are noises produced by the mouth at the beginning and end of vowel sounds.

SUMMARY OF PRINCIPLES IN CHAPTER XIX

Sound, in physics, is a vibratory motion transmitted through air or other gases, liquids, or solids.

Velocity of sound in air is about 1100 feet per second.

(Accurately it is 1087 ft. per sec. at 0° C., and it increases about 2 ft. per sec. for each degree C. rise.)

Wave length = distance from crest to crest (or from condensation to condensation).

Frequency = number of waves passing a given point in one second.

Velocity = frequency × wave length.
Loudness of sound varies inversely as the square of the distance.
***Intensity*, or loudness, depends on *amplitude*.**
***Pitch* (of musical tone) depends on *frequency*.**
***Quality* (of musical tone) depends on *wave form; i.e.*, on number and prominence of *overtones*.**
Pitch of a string (1) rises when length is *decreased*,
(2) rises when tension is *increased*,
(3) is higher for small, light strings.
Length of open pipe = $\frac{1}{2}$ wave length of fundamental.
Length of closed pipe = $\frac{1}{4}$ wave length of fundamental.

QUESTIONS

1. How can the pitch of the sound from a phonograph be raised?

2. What causes a difference in the pitch of an organ pipe between a hot day in summer and a cold day in winter?

3. How can a bugler produce notes of varying pitch on an instrument of unchanging length?

4. Why is it better to bow a violin string near one end rather than in the middle?

5. Is any difference in the quality of a violin tone noticeable when the bow is moved nearer the finger board? Why?

6. A distant band sounds much the same, except for loudness, as a band near by. What does this indicate about the velocity of sounds of different wave lengths?

7. When an electric-light bulb breaks, there is a loud crash. Why?

8. A man has two open organ pipes which are exactly alike. He saws off a little from the end of one. Explain what is heard when they are both sounded together.

9. There is an old saying that "if you can count three between a flash of lightning and its thunderclap, the storm is not dangerously near." According to this, how far away must the thunder cloud be for safety?

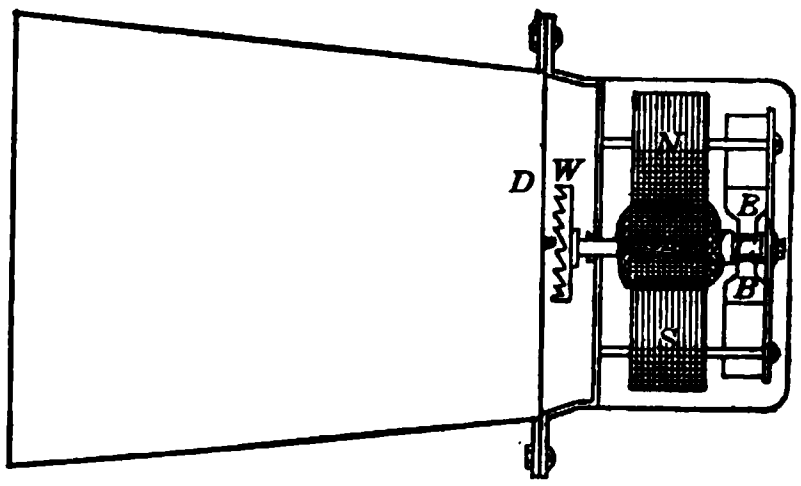


Fig. 478. A common form of automobile horn.

10. Explain how sound is produced by the form of automobile horn shown in figure 478.

PRACTICAL EXERCISES

1. The mechanism of the piano and the piano player. Examine the wires and study the relations of their sizes, lengths, and tension to pitch. How is a piano tuned? Make diagrams to show the key action, the keyboard, and octaves. What is the purpose of the black keys? What is the action of the pedals? What is the *even-tempered scale?* Find out how the air pressure in a piano player controls the key action.

2. The phonograph in business. Find out how the phonograph is used in business offices to save the time of stenographers. Discuss the advantages and disadvantages connected with its use.

3. The automobile muffler. Why is a muffler used? How is it constructed? Where is it located on an automobile? How does it work?

4. Musical pitch. Look up the history of musical pitch in an encyclopaedia or in *Helmholtz's* Sensations of Tone, trans. by Ellis (Longmans). What is meant by the statement that certain people "have absolute pitch"? If you know of such a person, test the accuracy of his pitch perception by varying the speed of a phonograph and measuring its revolutions per minute.

5. Vowel sounds. Find out from *Miller's* Science of Musical Sounds (The Macmillan Co.) how one vowel sound differs from another even when spoken or sung with the same pitch and loudness. What bearing have these differences on the art of singing?

CHAPTER XX

ILLUMINATION: LAMPS AND REFLECTORS

Illumination — law of inverse squares — standard lamps and candle power — Bunsen photometer — foot candles — laws of regular reflection — plane mirrors —concave mirrors — convex mirrors — graphical construction of image — size of image — the mirror formula.

423. Problem of illumination. We have to do so much of our work and play by lamplight, that we ought to know something about illumination. Of course the first essential is to have enough light to see things distinctly. Furthermore, experience shows that we may have enough light and yet not be able to distinguish the position and shape of objects well, because the lamps are not properly distributed to cast such shadows as we are accustomed to. Then there is the very difficult problem of getting lamplight which will give colored objects the same appearance as in daylight. Finally, we have to protect our eyes from the glare of modern powerful electric and gas lamps, which are likely to give us too much light in spots. Besides these physical aspects of the problem of illumination, there is the economic question of its cost.

424. Light advances in straight lines. Everyone knows that it is impossible to see around a corner. This is because *light under ordinary circumstances advances in straight lines.*

If we set up in a darkened room a screen and a lamp, as shown in figure 479, with an opaque screen pierced by a pinhole in between, we see an inverted image of the fila-

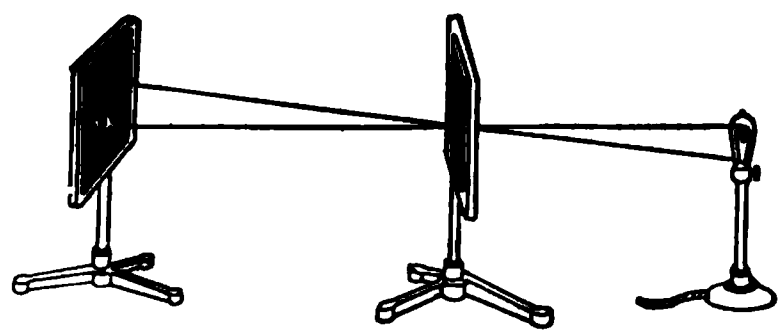


Fig. 479. Light passes through pinhole and advances in straight lines.

ment. This shows that the light goes through the hole in straight lines. Simple " pinhole " cameras are sometimes made on this principle.

The precise measurement of angles by surveyors depends upon the fact that light comes from the distant object to the observer's instrument in straight lines.

Another consequence of this fact is the formation of a shadow when an opaque object obstructs the passage of light. The edge of the shadow is, however, a sharply defined transition between light and dark, only when the source of light is very small. For example, the shadows cast by an arc lamp are more sharply defined than those cast by a gas flame or a Welsbach mantle. This is also true of the shadow cast by the earth, as shown in figure 480. The region *A* is in the full shadow and is called the **umbra**, while in the region *BB*, on either side, the light grades off from full shadow to full illumination. This region is called the **penumbra.** When the moon *M* happens to get wholly inside the umbra, we have a *total* eclipse. When the moon is partly in the penumbra, the eclipse is *partial.*

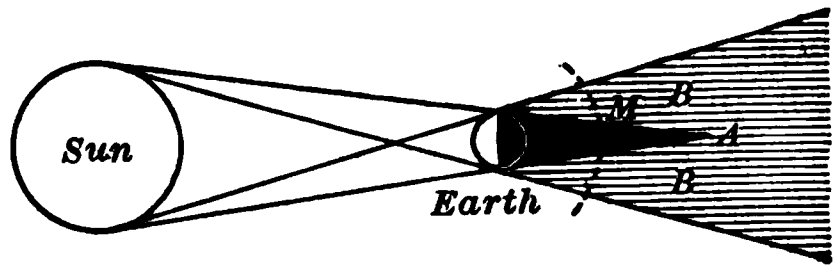


Fig. 480. Shadow cast by the earth.

425. Intensity of illumination: law of inverse squares. It scarcely needs to be stated that a book is more brilliantly illuminated when it is held near a lamp than when it is held far from the same lamp. In other words, the intensity of illumination, that is, the amount of light falling on a unit area, decreases when the distance increases.

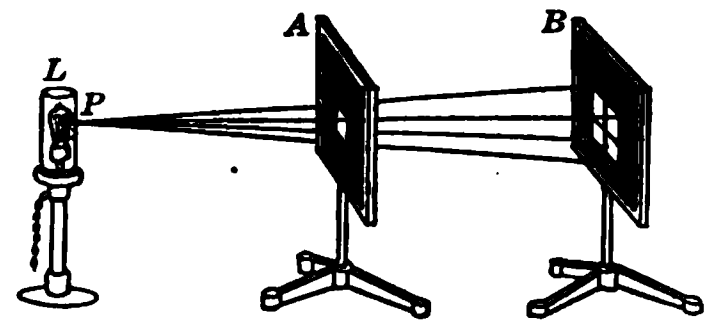


Fig. 481. Illumination decreases as the square of the distance.

Let a cylinder of sheet metal which has in it a small pinhole *P* (Fig. 481) be set up about a lamp, so that the source of light may be

considered a point. Then, *one foot* away, let us put a piece of cardboard *A* which has a hole in it one inch square. At a distance of *two feet* from the pinhole, we put a screen *B*. It is evident that the light which passes through the inch hole in *A* is spread at *B* over a 2-inch square; that is, over 4 square inches. If we move the screen *B* so that it is 3 feet from *P*, the light which passes through the inch hole at *A* is spread over a 3-inch square; that is, over 9 square inches. The areas of these squares increase as the square of the distance. But the amount of light falling on each total area is the same. Therefore the amount on each square inch decreases as the square of the distance.

Intensity of illumination (like the intensity of sound and for the same reason) varies inversely as the square of the distance.

This law assumes that the source of light is a point, and that the surface is placed at right angles to the rays of light. In all practical cases, however, the source of light is a surface, or region, every point of which is giving light, and in such cases this law is only approximately true. When the receiving surface is inclined (Fig. 482), it does not receive as much light per square inch as when held at right angles.

Fig. 482 Illumination on an inclined surface is less than when the surface is at right angles

426. Luminous intensity of a lamp. In computing the amount of light received on a given area, we have to consider not only the distance from the source, but also the **luminous intensity** of the lamp itself. A room, for example, is much more brilliantly illuminated by a modern electric or gas lamp than by a kerosene lamp. Since there are now many different forms of lamps on the market, it is highly important that we have some way of measuring their luminous intensities. To do this we must have a **standard lamp** and some instrument for the comparison of lamps, that is, a **photometer.**

427. The standard lamp. Although many standard lamps have been proposed, none is altogether satisfactory. The

oldest standard lamp, which is still used in calculation but seldom in actual practice, is the English standard candle, a sperm candle made according to certain specifications. The illuminating power of a horizontal beam from this candle is called a **candle power.**

The present value of the candle power as used in the United States is that established by a set of standard incandescent

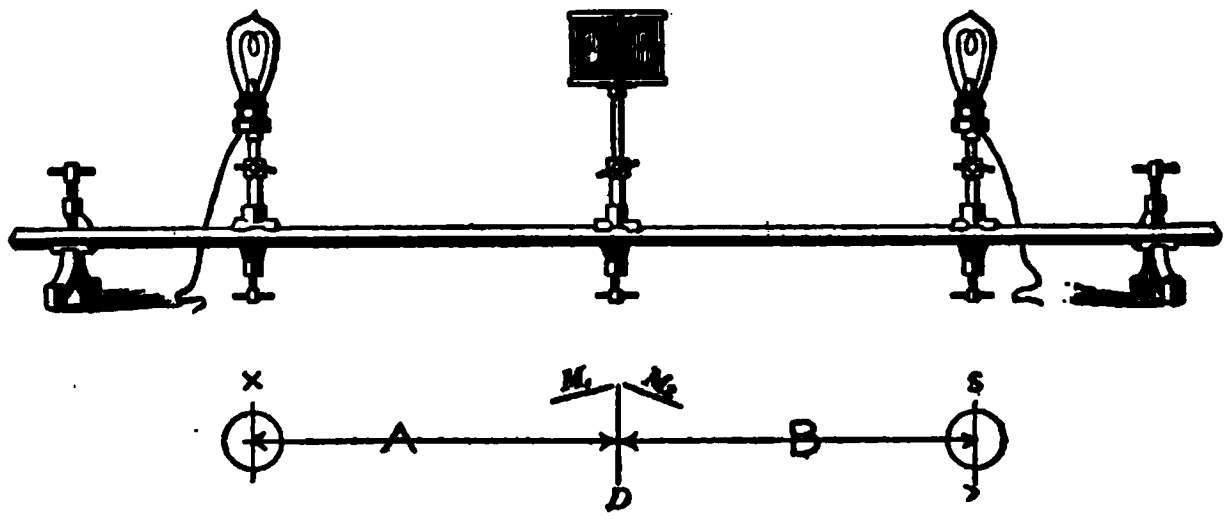


Fig. 483. Bunsen photometer.

lamps maintained at the Bureau of Standards in Washington, D. C. This unit of intensity is called the **international candle**, and has been accepted by England and France. In Germany the legal unit of intensity is the **Hefner**, which is equal to 0.9 international candles.

In testing gas, sperm candles are still used in routine work, although the intensity of so-called standard candles may vary by as much as 5 per cent. For more accurate work, the Harcourt pentane lamp is coming into use. This burns a mixture of air and pentane vapor and has an intensity of 10 candles.

The ordinary open gas flame consumes from 5 cubic feet of gas per hour upward, and gives from 15 to 25 candle power. In Massachusetts the legal standard for gas is that it shall give 15 candle power in a burner consuming 5 cubic feet an hour. Welsbach lamps consume about 3 cubic feet of gas per hour and give 50 to 100 candle power.

428. Bunsen photometer. This is an instrument for comparing the illuminating power of a beam from a given lamp with the illuminating power of a horizontal beam from a standard lamp. This "grease-spot" photometer (Fig. 483) was in-

vented by the great German chemist, Robert Bunsen. It consists essentially of a white paper screen with a translucent spot in the center, which transmits light freely. The screen is placed between the lamps to be compared, so that one side is lighted by one lamp and one by the other. If the screen is lighted more on one side, that side appears bright with a dark spot in the center; while the other side is darker with a bright spot in the center. If the two sides are equally illuminated, the spot disappears, or at least looks equally bright on each side. The grease-spot screen is inclosed in a box (Fig. 484), which is open at the ends A and B toward the lamps to be compared. The eye is held in front at E. Two mirrors m_1 and m_2 are placed on either side of the screen, as indicated in the figure, so that the two sides of the screen can be seen at the same time.

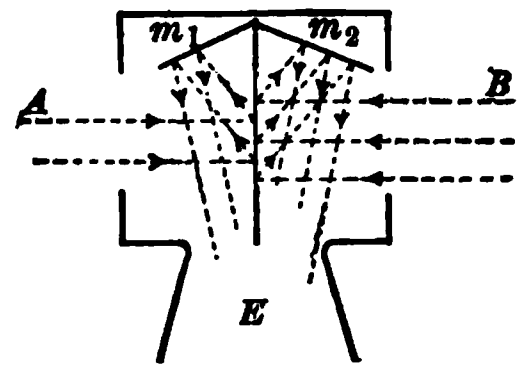


Fig. 484. Bunsen light box with screen.

429. Use of Bunsen photometer. The photometer must be used in a dark room or else in a light-tight box. The lamp X to be tested is placed at one end of the photometer bar and the standard lamp S at the opposite end. The screen is then moved back and forth until a position is found where it is equally illuminated on both sides, and the distances A and B are measured.

It is evident that if the distances A and B are equal, the candle powers of the two lamps are the same. If the distances are not equal, *the lamp which is farther from the screen has the greater candle power*. Furthermore, since the intensity of illumination decreases as the square of the distance, *the candle powers of the two lamps are directly proportional to the squares of their distances from the screen.*

For example, if a lamp of candle power X 100 centimeters from the screen balances a 16 candle-power lamp 80 centimeters away,

then $$\frac{X}{16} = \frac{(100)^2}{(80)^2}$$

and $$X = 25 \text{ candle power.}$$

430. Distribution of light. No lamp gives light uniformly in all directions. Thus in the ordinary kerosene lamp the burner and oil reservoir cut off the light which would be radiated downward from the flame; and if the flame is broad and thin, it will give more light broadside on than edgewise. Similarly, an incandescent lamp gives different intensities in different directions because of the shape of the filament.

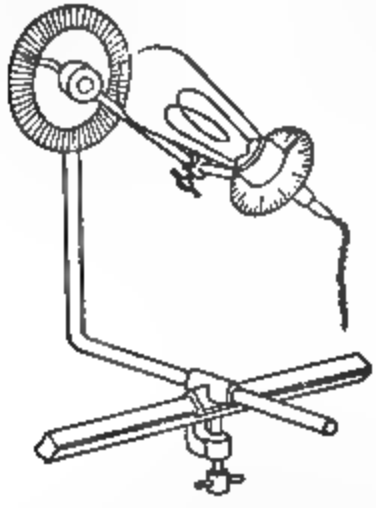


Fig. 485. Apparatus for tilting lamp to be tested.

Since an incandescent lamp can be easily turned in any position (Fig. 485), it is not difficult, with the Bunsen photometer, to measure its candle power in various positions. If the candle power is measured in several directions in a horizontal plane, and the results of the tests averaged, the result is called its **mean horizontal candle power.** Such tests show that the candle power in various directions in a horizontal plane does not vary very much.

If the lamp to be tested is tilted at different angles in a vertical plane, the results show that the lamp has very low candle power directly under the tip. The results of such tests may be best shown graphically by a diagram (Fig. 486 A). In this figure the intensity of the light in various directions in a vertical plane is indicated by the curve, which varies in its distance from the center of the concentric circles according to the intensity of the light. Thus, the candle power directly under the tip of the bulb (0°) is a little under 8, while horizontally (90°) it is 16 candles.

When it is desirable to throw as much light as possible directly downward, some kind of reflector or shade is used. Figure 486 B shows the vertical distribution of light when the bulb is fitted with a special shade. From this curve it will be seen that the horizontal intensity is cut down to 6 candles, while the downward intensity runs over 50 candles. Such shades, made

Fig. 486. Photometric curves (*A*) of a bare incandescent lamp and (*B*) of the same lamp with a reflector.

in a great variety of forms to give different desirable distributions, make it possible to work out scientifically the problem of lighting a given room or workshop efficiently.

431. Measurement of intensity of illumination. We have just seen that the unit of intensity for a source of light is the international candle. The illumination which such a standard candle throws upon a surface placed one foot away and at right angles to the rays of light is called a **foot candle.** It is the **unit of intensity of illumination.** Evidently,

$$\textbf{Illumination (foot candles)} = \frac{\textbf{candle power}}{\textbf{distance squared (ft.)}^2}.$$

FOR EXAMPLE, a 16-candle-power lamp would illuminate a surface placed 1 foot from it with an intensity of 16 foot candles. Again, if the lamp were a 32-candle-power lamp and the object were 4 feet away, the intensity of illumination would be $\frac{32}{(4)^2}$, or 2 foot candles.

In these examples we have assumed that there is only one source of illumination, and that the surface is perpendicular to the rays of light. In practice this is almost never the case, so that the problem of computing the intensity of illumination on any given surface is very difficult.

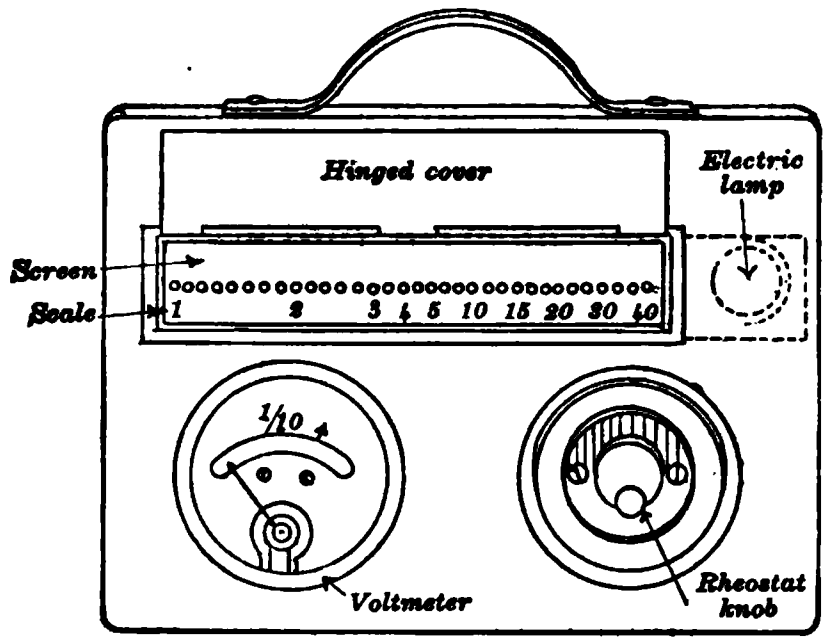


Fig. 487. A foot-candle meter for measuring illumination directly.

Figure 487 shows a very simple instrument called a **foot-candle meter,** for measuring directly the intensity of illumination at any place. The most essential part of the instrument is a screen with a row of translucent spots which are illuminated from below by a tiny electric lamp placed at one end. In order to make sure that the lamp is always at the same intensity, there is an adjustable rheostat connected in series with the battery, and a sensitive voltmeter, which registers the voltage supplied to the lamp. To use the meter, one merely

adjusts the rheostat until the voltmeter indicates that the lamp is getting the required voltage; then one selects on the screen the round spot which most nearly disappears, that is, appears to be of the same brightness as the white screen surface; and finally, one reads off the

Fig. 488. The illuminated screen of a foot-candle meter.

number of foot candles from the point on the scale which is beneath this spot. For example, the screen shown in figure 488 indicates 10 foot candles.

432. How much illumination is needed? The amount of illumination needed to furnish "good light to see by" varies greatly with conditions. For example, drafting rooms, theater stages, and stores require about 4 foot candles; while churches, residences, and public corridors may need but 1 foot candle. Excessive light is as undesirable as insufficient light. Exposed light-sources of great brilliancy (more than 5 candle power per square inch) constitute a common source of eye trouble. To avoid this, electric bulbs should be frosted and distributed in small units, or covered with shades which diffuse the light, or else concealed entirely from view. In the latter case the illumination is obtained by light reflected from the ceiling and walls. This indirect system of illumination gives by far the best light, especially for large rooms in public buildings; but it costs more than other systems, and is to be regarded as a luxury.

PROBLEMS

1. If the page of your book is sufficiently illuminated at a distance of 3 feet from an 8-candle-power lamp, how many candle power will be needed when you move 2 feet farther away?

2. If a photographic print can be made in 30 seconds when held 3 feet from a light, how long an exposure will be needed when the print is 6 feet away?

3. A 4-candle-power lamp is 120 centimeters from a screen. How far away must a 16-candle-power lamp be to illuminate the screen equally?

4. In measuring the candle power of a lamp, a Hefner standard lamp (0.90 candle power) is 50 centimeters from the grease spot of a Bunsen photometer, and the lamp to be tested balances it when 150 centimeters away. How many candle power has the lamp?

5. Two lamps give 16 and 32 candle power respectively, and are 200 centimeters apart. Where between the lamps may a grease-spot photometer screen be placed so that its two sides are equally illuminated?

6. What is the illumination in foot candles on a surface 5 feet from an 80-candle-power lamp?

7. The necessary illumination for reading is about 2 foot candles. How far away may a 16-candle-power lamp be placed?

8. If the lamp with the special shade described in section 430 is to be hung above a reading table, how high should it be placed? (See curve of distribution, Fig. 486 *B*.)

9. Compare the expense of illumination with gas and electricity. A Welsbach gas lamp burning 5 cubic feet of gas per hour gives 100 candle power. The gas costs 90 cents per 1000 cubic feet. A 40-watt Mazda lamp gives about 32 candle power. Electricity is 10 cents per kilowatt hour. (Find the expense of each lamp per hour, and then the expense of 1-candle-power hour for each.)

10. A newspaper is sufficiently illuminated when held 2 feet from an 8-candle-power incandescent lamp. How far from a 40-candle-power Welsbach mantle should the paper be to receive the same illumination?

11. The electric lamp whose distribution of light is shown in figure 486 *A* is placed 4 feet above and 4 feet to one side of a horizontal table. Find the illumination (foot candles) on the surface of the table.

12. What is the illumination upon a surface 50 yards from a 1000-candle-power arc lamp? Does the illumination in this example meet the desirable minimum of 0.04 foot candles for a sidewalk?

PRACTICAL EXERCISE

Measurement of illumination. By means of a foot-candle meter, measure the illumination on your study table at home, on the dining-room table, and on the living-room table. Compare your results with the figures recommended by illuminating engineers. (See Instructions accompanying the instrument.)

433. Reflectors, regular and irregular. We already know that we are able to see most objects about us by the light which they reflect to our eyes. The surfaces of most objects are rough, and so the light striking them is reflected in an irregular fashion, as shown in figure 489. This kind of reflection, or turning back, of the light we call **diffused reflection.** Thus the light striking a piece of paper or unvarnished wood is scattered. If, however, light strikes a flat metallic surface, carefully polished so that it is very smooth, the light enters the eye as though coming directly from a distant object, instead of from the reflecting surface. This is called **regular reflection**, and is illustrated in figure 490, where *mm* is the reflecting surface, or mirror. The line *OP* indicates the direction of the light falling on the mirror, and *PE* indicates the direction of the reflected light.

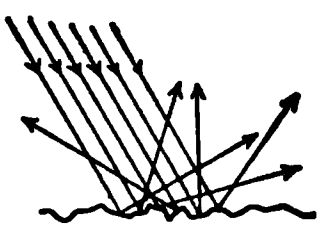


Fig. 489. Diffused reflection from an irregular surface.

434. Law of reflection. When light comes through a small opening, the stream of light is called a **beam.** A very narrow beam is called a **ray.*** When a beam of light comes from a very distant source, such as the sun, the rays of which it is composed are parallel, and so it is called a parallel beam.

In figure 490, let *OP* be the direction of a parallel beam striking the mirror *mm* obliquely, and *PE* that of the reflected beam. If a line *nn*, called the **normal**, is drawn perpendicular to the reflecting surface at the point *P*, the angle *i* between the normal and the direction *OP* of the incident beam is called the **angle of incidence**; and the angle *r* between the normal and the direction of the reflected beam is called the **angle of reflection.**

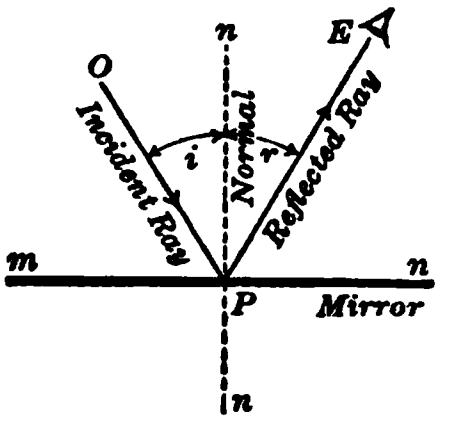


Fig. 490. Regular reflection from a smooth surface.

Careful experiments have shown that,

I. *The incident ray, the normal, and the reflected ray lie in one plane.*

II. *The angle of incidence is equal to the angle of reflection.*

* A more accurate definition of a "ray" will be given in section 453 of the next chapter.

435. Images in a plane mirror. We all know that a person standing in front of a plane mirror sees his own image and that of the objects about him as if they were *behind the mirror*. In figure 491 we see that light coming from any point A of an object is reflected by the mirror to the eye as if coming from a point A' back of the mirror. Similarly, light coming from a group of points (an object AB) seems to come from a similar group of points (the image $A'B'$) back of the mirror. The group of points from which the light *appears* to come is called the **image** of the object. A line AA' drawn from any point in the object to its corresponding point in the image is perpendicular to, and is bisected by, the mirror mm.

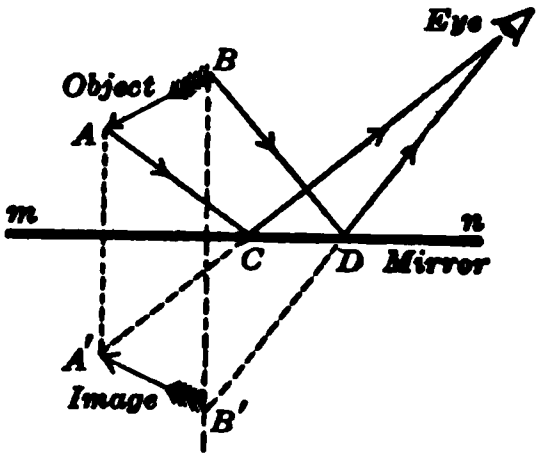


Fig. 491. Image in a plane mirror.

In general, *an image in a plane mirror is the same size as its object, and as far behind the mirror as the object is in front.*

Indeed, such an image is so much like a real object that conjurors often make use of the illusions due to the invisibility of a well-polished mirror. Since, however, the image is reversed from right to left, conjurors never allow a printed page or clock face to be seen in a mirror.

436. Uses of plane mirrors. Good mirrors for household use are made of plate glass backed by a thin coating of silver or mercury. Very little of the light is reflected from the front surface of the glass; the rest is reflected from the metal back. Large plate-glass mirrors are sometimes placed on the walls of public rooms to give an impression of *spaciousness*.

In scientific instruments a very small mirror is often attached to a rotating part, such as the coil of a galvanometer. Such a mirror will turn a reflected beam of light through *twice* the angle through which the mirror itself is turned.

A rotating mirror M_1 is an essential part of the **sextant** (Fig. 492) which mariners use to get the altitude of the sun. Attached to the frame is another plane mirror M_2, only half of which is silvered; the

other half, unsilvered, is transparent. There is also a telescope T attached to the frame and pointing to the half-silvered mirror. The graduations on the circle are made so as to read off directly the degrees in the angle to be measured. In determining the angular altitude of the sun above the horizon, the mirror M_1 is rotated until the image of the sun seen by double reflection in M_1 and M_2 coincides with the image of the horizon seen directly through the unsilvered portion of the stationary mirror M_3.

Fig. 492. Sextant used to measure angles in surveying and navigation.

Questions and Problems

1. Would a perfectly transparent body be visible? Explain.

2. Could you see a perfect reflecting surface? Explain.

3. If a ray of light strikes a plane mirror so that the angle between the ray and the mirror is 25°, what is the angle between the incident and reflected rays?

4. If the mirror in problem 3 is turned 1°, so that the angle between the incident ray and the mirror becomes 26°, through how many degrees has the reflected ray been turned?

5. A tree stands on the edge of a quiet pond and is inclined at an angle of 60° to the surface of the water. Construct the image of the tree seen in the water.

6. A woman 5 feet 6 inches tall stands 4 feet in front of a vertical mirror and sees her entire image. What is the shortest mirror which can be used for this purpose? Construct a diagram to prove your answer.

7. Two plane mirrors are placed at right angles to each other and an object is placed between them. How many images will be seen? Draw a diagram to show the position of the images.

8. Explain with the aid of a diagram the fact that parallel mirrors give rise to an indefinite number of images all on the same line passing through the object. Try it.

9. How can you determine the thickness of a plate-glass mirror by placing a pencil point upon it?

10. A room 20 feet square has plane mirrors on opposite walls. A

man in the room holds a lamp close to his head. Where should he stand so as to be as near as possible to the twice reflected image of the lamp in the mirrors?

437. Curved mirrors. A curved mirror is usually spherical; that is, it is a portion of the surface of a sphere. If it is a portion of the outer surface, it is called a **convex** mirror; if it is a portion of the inner surface, it is called a **concave** mirror. The center of the sphere of which the curved mirror is a portion is called the **center of curvature** (*C* in Fig. 493). The line *CM* connecting the middle of the mirror *M* with the center of curvature *C* is called the **principal axis.** Any other straight line through the center of curvature, such as *CS*, is called a **secondary axis.** It will be noticed that any axis is perpendicular to the reflecting surface.

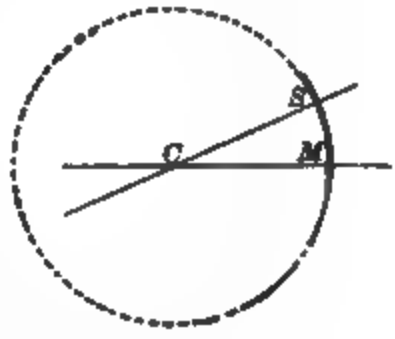


Fig. 493. Center of a curved mirror.

438. Principal focus. When a beam of light parallel to the principal axis strikes a concave mirror, the rays are so reflected as to pass through, or very close to, a single point (Fig. 494). This point is called the **principal focus** of the mirror. It may be defined as *that point where all rays parallel to and near the principal axis of a mirror meet after reflection.* The distance from the principal focus to the mirror is called its **focal length** and is one half its radius of curvature.

Fig. 494. Concave mirror converges parallel rays.

We may show that the principal focus is located half way between the mirror and its center of curvature. Suppose the ray *QP* in figure 495, parallel to the axis *AB*, strikes the mirror at the point *P* and is reflected back in the direction *PF*, so as to make the angle of incidence *i*

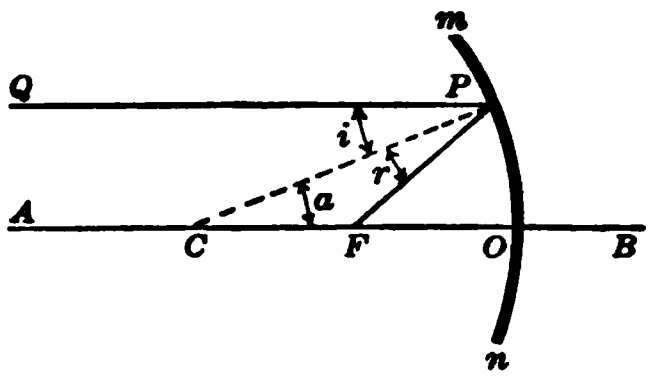


Fig. 495. Location of principal focus.

equal to the angle of reflection r. Since QP and AB are parallel lines, the angle i is equal to the angle a. Therefore the angle a must be equal to the angle r, and $CF = PF$. But when P is near O, PF is nearly equal to FO, which means that F is about midway between C and O. It can be proved that the principal focus, which is very close to F, is exactly halfway between C and O.

All the rays parallel to the principal axis of a concave spherical mirror do *not* meet exactly at the same point after reflection. This failure of the rays to converge accurately at a point is called **spherical aberration.** This imperfection is slight when only a small portion of a sphere is used as a mirror. Spherical aberration in a large mirror is shown in figure 496, where it will be observed that only the central rays are reflected through the focus F, while the rays which strike the mirror near the edge are reflected decidedly to the right of F.

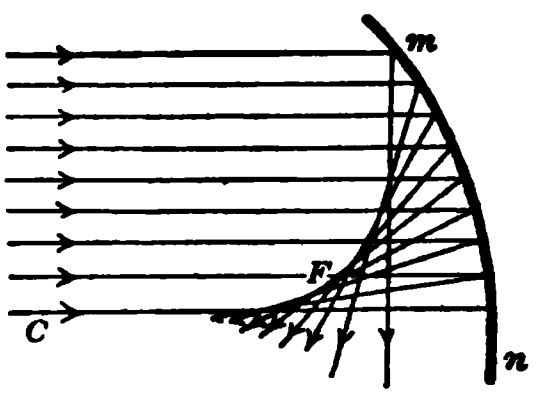


Fig. 496. Aberration in a spherical concave mirror.

It is sometimes necessary, as in the case of a searchlight, to take the divergent rays of an arc lamp and reflect them all in one direction. This can be done roughly with a concave spherical mirror, by putting the arc at the principal focus; for then the rays travel the same paths as above, but in the opposite direction. To avoid spherical aberration, however, a **parabolic mirror** (Fig. 497) is generally used.

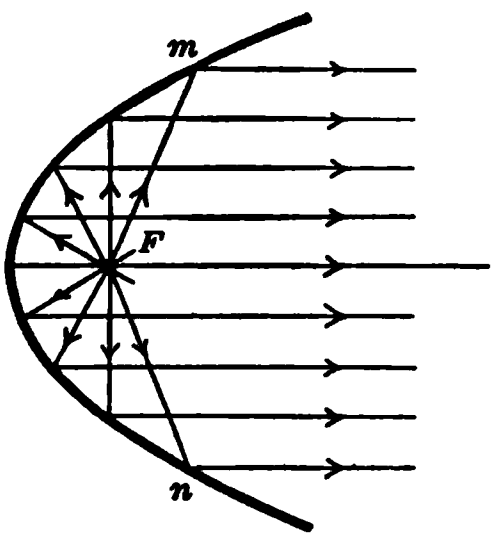


Fig. 497. Parabolic mirror.

439. Uses of concave mirrors. The **ophthalmoscope** is a concave mirror with a little hole in it. With this instrument a physician can reflect light from a lamp into a patient's

Fig. 498. Reflecting telescope, with a concave mirror, 100 inches in diameter, at Mount Wilson Observatory, Pasadena, California. The two large drums at the ends of the solid beam float in mercury. Notice the movable observing platform in the upper right-hand corner.

eye, nose, or throat, and at the same time look through the hole into the cavity thus illuminated.

A certain type of telescope, called a **reflecting telescope** (Fig. 498), consists of a long tube with a concave mirror at one end, which forms an image of a distant object. The only purpose of the tube is to support near its open end an eyepiece or magnifying glass through which the image can be advantageously examined.

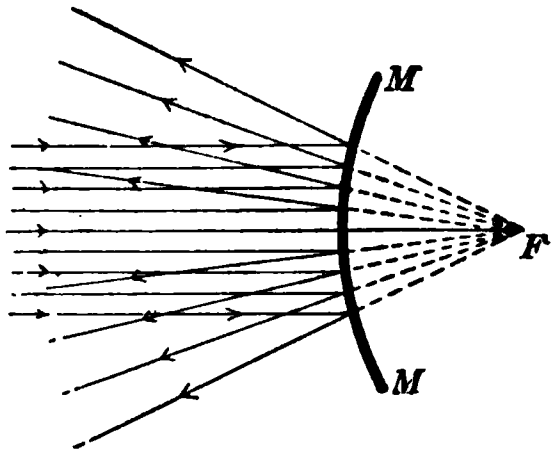


Fig. 499. Convex mirror and virtual focus.

In a **compound microscope** light from a window or lamp is concentrated upon the object to be examined, by means of a concave mirror.

Concave mirrors are extensively used in **searchlights** and **headlights.**

440. Convex mirror. When a beam of light parallel to the principal axis strikes a convex mirror (Fig. 499), the rays are reflected as if they came from a point F which is behind the mirror, and half way between C, the center of curvature, and the mirror. The point F is called a **virtual focus,** because the rays do not actually pass through it, but simply *look as if* they had come from it. In the case of the concave mirror the rays do actually pass through the point F; this is shown by the fact that a large concave mirror of short focal length causes so great a concentration of the sun's radiant energy that paper and wood may be ignited if placed at F. Such a focus is a **real focus.**

The image of any object in front of a convex mirror appears to be behind the mirror and seems to be erect but smaller. For this reason small convex mirrors are often fastened to the windshields of automobiles to show the driver what is coming from behind.

441. Construction of images. It is possible to learn a great deal about the position and size of images formed by mirrors, by carefully constructing diagrams to show the paths of the rays of light.

Suppose *mn* in figure 500 is a **convex mirror**, and *AB* an object. Let us draw *AC*, a ray normal to the mirror. This ray will be reflected directly back on itself at *P*. Again let us draw *AD* parallel to the principal axis. This ray will be reflected as if it came from *F* (the focus). The image point of *A* will be at *A'* where these two reflected rays cross. In the same way *B'* is located.

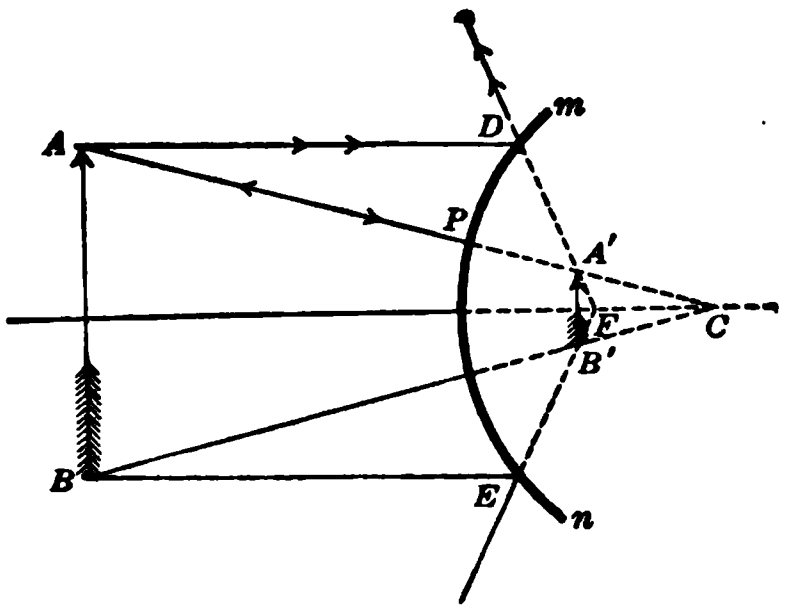


Fig. 500. Construction of image in a convex mirror.

This construction shows that the image in a **convex mirror** always seems to be **behind** the mirror and **smaller** than the object. It is **erect** and **nearer** the mirror than is the object. *It is always a virtual image.* Thus a person sees a **virtual** image of his face in a polished ball. It is always right side up and of small size.

Suppose *mn* (Fig. 501) is **a concave mirror**, of which *C* is the center of curvature. Let *AB* be an object which is placed beyond the center of curvature. To determine the position of the image, let us trace two rays from *A*. If *AP* is one such ray passing through *C*, it will hit the mirror perpendicularly and be reflected directly back along the line *PC*. If the other ray from *A* is *AD*, parallel to the axis, it will be reflected so as to pass through the focus *F*. The point *A'*, where they intersect after reflection, is the image of *A*. In a similar way the image of *B* is located at *B'*; so the image of the arrow *AB* will be the arrow *A'B'*.

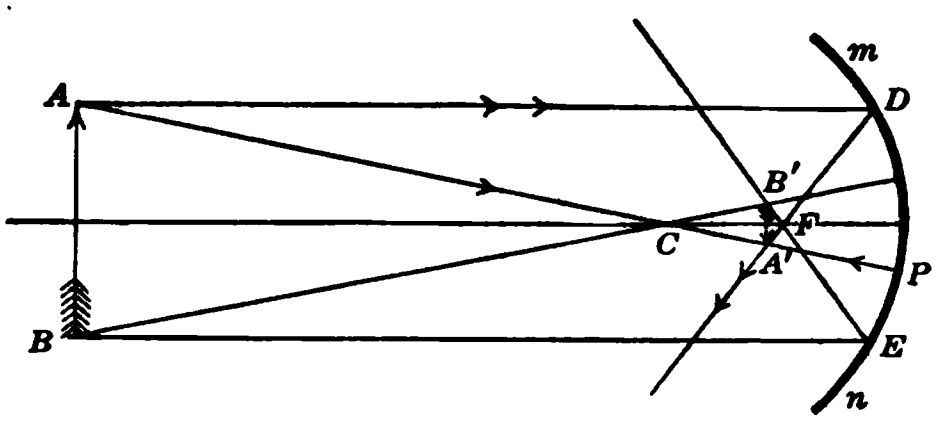


Fig. 501. Construction of image in a concave mirror.

It will be seen that when the object is **beyond the center of curvature**, the image is **inverted** and **in front** of the mirror. Since the rays of light from *A* really do pass through *A'*, the image is **real.**

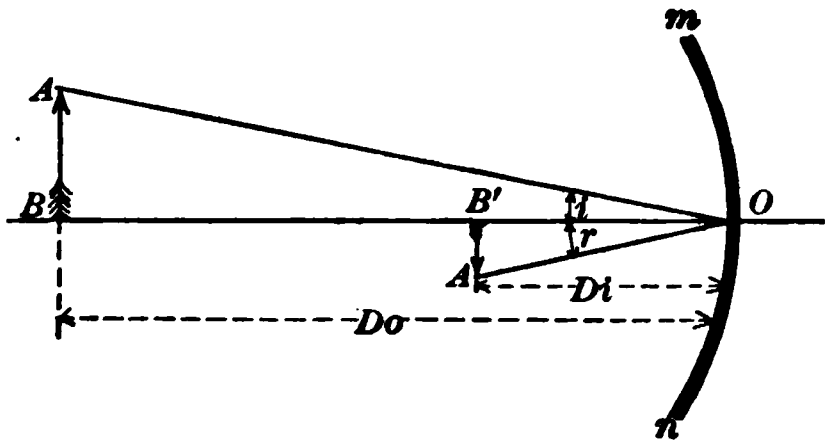


Fig. 502. To get size of a real image.

442. Size of a real image. Let us draw the ray AO and its reflected ray OA' (Fig. 502). From the law of reflection, the angle of incidence i is equal to the angle of reflection r. Therefore, the right triangles AOB and $A'OB'$ are similar, and their corresponding sides are in proportion. That is,

$$\frac{A'B'}{AB} = \frac{B'O}{BO} = \frac{Di}{Do}$$

The size of the image is to the size of tne object as the distance of the image from the mirror is to the distance of the object from the mirror.

443. Conjugate foci. We have seen in figure 501 that when A is the object point, the image point is at A'. But if A' is the object point, the image point is at A; for the rays will travel the same paths in the other direction. For example, if a lamp were put at AB, an inverted smaller image would be formed on a screen placed at $A'B'$; also if the lamp were put at $A'B'$, the image would be inverted, larger, and located at AB (Fig. 503).

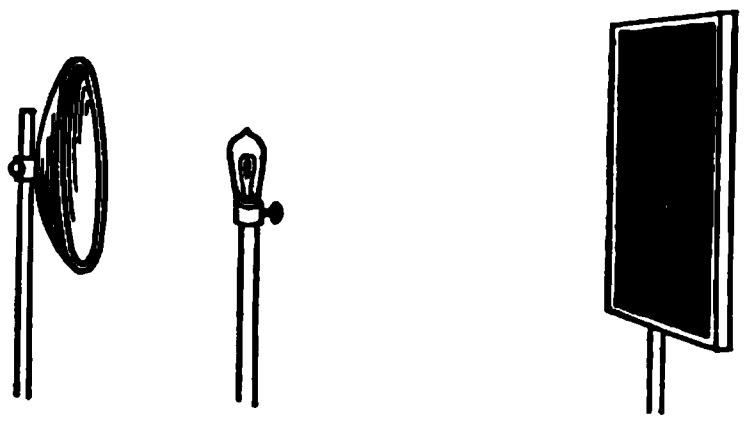


Fig. 503 Conjugate foci of a concave mirror.

Two points, so situated that light from one is concentrated at the other, are called **conjugate foci.** For example, B and B' in figure 501 are wo such points and therefore are conjugate foci.

444. Virtual image in a concave mirror. We have just seen that when the object is beyond the center of curvature,

the image is between the principal focus F and the center of curvature C. Also when the object is between F and C, the image is beyond C. In both cases, the image is real; *the image is always real when the object is outside the principal focus F.*

When, however, the object is placed **inside the principal focus**, that is, between F and the mirror as shown in figure 504, the image is **behind** the mirror, **erect, enlarged,** and **virtual.**

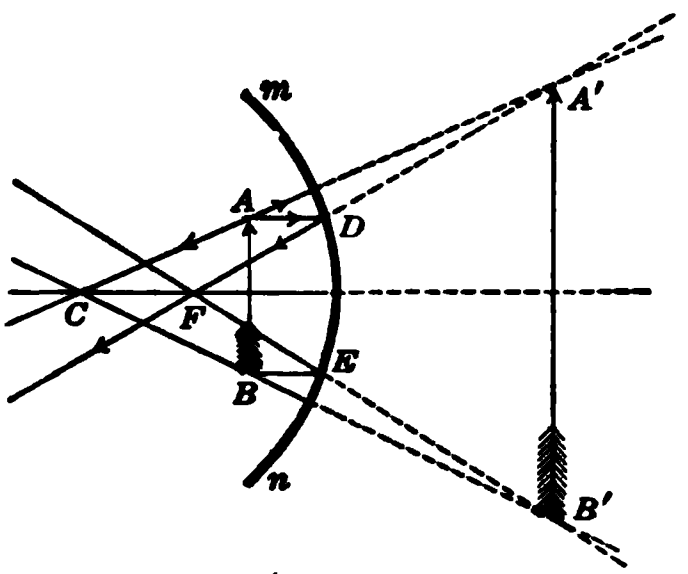


Fig. 504. Construction of virtual image in concave mirror.

To show this we may, as before, trace two rays from the point A, one parallel to the axis, which is reflected through F, and the other perpendicular to the mirror, which is reflected back on itself through C. They will diverge after reflection and must be produced backward to find the point of intersection A'. The image A' is a virtual image, because the light from A does not actually pass through A'.

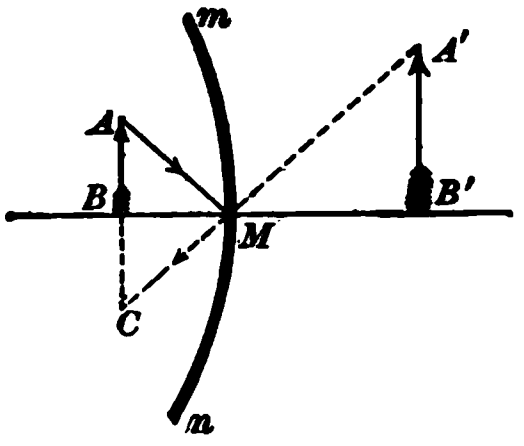


Fig. 505. To get size of a virtual image.

445. Size of a virtual image. Since every ray from A (Fig. 505) is reflected so as to seem to come from A', the ray from A to M, the middle of the mirror, will be reflected in the direction $A'MC$. Since the angles of incidence and reflection are equal,

$$\text{angle } AMB = \text{angle } BMC.$$

But $A'MB'$ and BMC are vertical angles and equal. So

$$\text{angle } AMB = \text{angle } A'MB'.$$

Therefore the right triangles AMB and $A'MB'$ are similar, and

$$\frac{A'B'}{AB} = \frac{B'M}{BM}.$$

So in this case, as before, the size of the image is to the size of the object as the image distance is to the object distance.

446. The mirror formula. Let O in figure 506 be an object on the axis, and OM any ray from O meeting the mirror at M. Draw the radius CM and construct the reflected ray MI, making angle CMC = angle CMI. Then I is the image of O. Since CM is the bisector of the angle OMI, it follows that

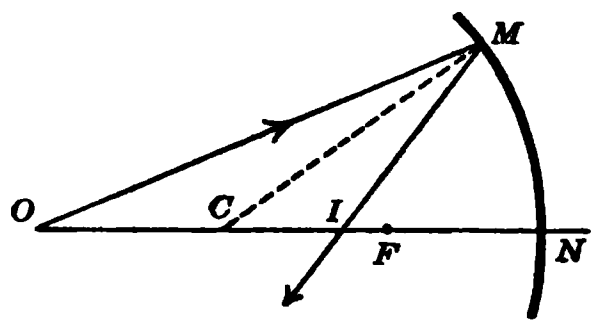


Fig. 506. Location of real images in concave mirror.

$$\frac{OM}{IM} = \frac{OC}{IC}. \qquad (1)$$

Let $IN = D_I$, and $ON = D_O$. When the aperture, that is, the angle MON, is small, we have the approximate relations

$$OM = ON = D_O, \text{ and } IM = IN = D_I.$$

Now, since $FN = f$,

$$OC = ON - CN = D_O - 2f$$
$$IC = CN - IN = 2f - D_I.$$

Substituting these values in the proportion (1), we have

$$\frac{D_O}{D_I} = \frac{D_O - 2f}{2f - D_I}$$

which reduces to $$D_I f + D_O f = D_O D_I.$$

Dividing by $D_O \times D_I \times f$, we have

$$\frac{1}{D_O} + \frac{1}{D_I} = \frac{1}{f}$$

where

D_O = distance of object from mirror,
D_I = distance of image from mirror,
f = focal length of mirror.

Stated in words

$$\frac{1}{\text{Object distance}} + \frac{1}{\text{image distance}} = \frac{1}{\text{focal length}}.$$

This equation gives us a useful relation between the distance of the object from the mirror, the distance of the image, and the focal length. If any two of these three quantities are known, the third can be calculated.

It can be proved that this equation holds as it stands for all cases of images either real or virtual, formed in a concave

mirror. If the value of D_i comes out negative for certain values of D_o and f, as it will when D_o is less than f, the meaning is that the image is behind the mirror; that is, the image is virtual. It can be shown that it holds also for convex mirrors, if the focal length f of a convex mirror is regarded as negative.

In the next chapter we shall see that this same equation holds for lenses.

PROBLEMS

1. An object is placed 15 inches from a concave mirror whose radius of curvature is 12 inches. How far from the mirror is the image? Is it real or virtual, erect or inverted?

2. If the object in problem 1 is 3 inches long, how long is the image?

3. An object is placed 12 inches from a concave mirror whose focal length is 8 inches. How far from the mirror is the image? Is it real or virtual, erect or inverted?

4. If the object in problem 3 is 2 inches long, how long is the image?

5. An arrow 1 inch long is placed 4 inches from a concave mirror whose radius of curvature is 12 inches. Find the position, length, and nature of the image.

6. If the image of a candle flame, placed 10 inches from a concave mirror, is formed distinctly on a screen 30 inches from the mirror, what is the radius of curvature?

7. How far from a concave mirror whose focal length is 2 feet must a man stand to see an erect image of his face twice its natural size?

8. Where must an object be placed to form, in a concave mirror whose focal length is 10 inches, a real image one half as long as the object?

9. The radius of curvature of a convex spherical mirror is 20 inches. Find the position of the image of an object 5 feet from the mirror.

10. Given a concave mirror whose radius of curvature is 90 centimeters; find two positions where an object can be placed and produce an image which is three times as long as the object.

SUMMARY OF PRINCIPLES IN CHAPTER XX

Intensity of illumination varies inversely as square of distance.

Candle powers of lamps giving equal illumination are directly proportional to the squares of their distances from screen. (That is, lamp *farther* away is *more* powerful.)

Unit intensity of illumination, or foot candle, is illumination due to a one-candle-power lamp one foot away.

$$\text{Illumination (foot candles)} = \frac{\text{candle power}}{\text{distance squared (ft.)}^2}.$$

In regular reflection:

I. Incident, normal, and reflected rays all in one plane.

II. Angle of reflection = angle of incidence.

Plane mirror: Image always behind mirror, erect, virtual, same size as object, and at same distance from mirror as object.

Principal focus of curved mirror (either concave or convex);
***Defined* as convergence point for rays parallel to axis of mirror,**
***Located* halfway between mirror and center of curvature.**

Concave mirror:

If object is *outside* focus, image is also outside focus, and center of curvature is between object and image. Image is inverted and real.

If object is *inside* focus, image is behind mirror, erect and virtual.

Convex mirror: Image always behind mirror, erect and virtual.

Mirror formula (holds for both concave and convex mirrors):

$$\frac{1}{\text{Object distance}} + \frac{1}{\text{image distance}} = \frac{1}{\text{focal length}}.$$

***Object distance* is always to be taken as *positive*.**
***Image distance; positive* for *real* images and *negative* for *virtual*.**
***Focal length; positive* for *concave* mirrors and *negative* for *convex*.**

Size rule (holds for both concave and convex mirrors):

$$\frac{\text{Length of image}}{\text{Length of object}} = \frac{\text{image distance (from mirror)}}{\text{object distance (from mirror)}}.$$

QUESTIONS

1. What is the difference between 16 candle power and 16 foot candles?

2. How can a Welsbach gas lamp consuming only 3 cubic feet of gas per hour give over 50 candle power, when an ordinary gas jet using 5 or more cubic feet per hour gives only about 18 candle power.

3. If light from a very distant object, such as the sun, falls on a concave mirror, where is the image formed?

4. How does the curve of a parabola differ from the arc of a circle?

5. How does the action of a parabolic mirror differ from that of a concave spherical mirror?

6. What is the danger in too great intensity of illumination?

7. Explain how the image of a man standing in front of a plane mirror which is tilted so as to make an angle of 45° with the floor appears horizontal.

8. A person looking into a mirror sees a very small image of his face upside down. What kind of mirror is it?

9. Show by a diagram how a tailor arranges two mirrors so that a customer can see the back of his coat.

10. Describe the changes in the position and nature of the image of a luminous point, as the point is moved from a great distance up to a concave mirror along its axis.

PRACTICAL EXERCISE

Automobile headlights. What type of electric lamp is legal for headlights in your state? Determine the focus of a headlight mirror (Fig. 507). By experiment find the effect of placing the lamp filament in front of the focus. Construct a diagram to show the reason for this effect.

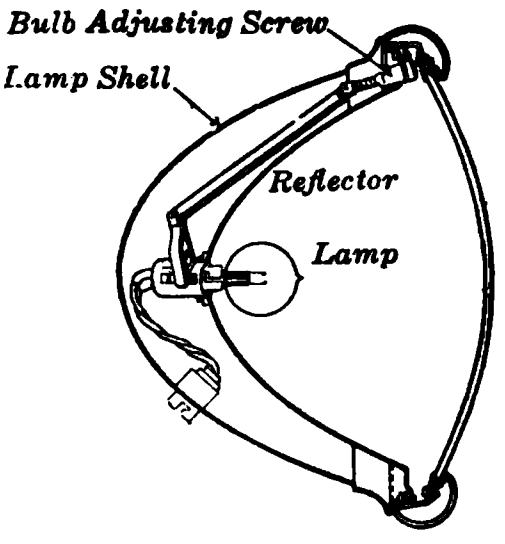


Fig. 507. Automobile headlight with parabolic mirror.

CHAPTER XXI

LENSES AND OPTICAL INSTRUMENTS

Refraction — law of refraction — speed of light — wave fronts — explanation of refraction — index of refraction as ratio of speeds — total reflection — prism — lenses — lens equation — size rule — defects of lenses.

Camera — eye — defects of eye — projecting lantern — motion pictures — magnifying glass — microscope — telescope — erecting telescope — opera glass — prism binocular.

447. Optical instruments. The human eye is the most common and at the same time one of the most remarkable optical instruments known. Human eyes are often imperfect in various ways, and have to be "corrected," or rather, aided in their work; for defective eyes themselves are seldom changed by spectacles or eyeglasses. These, too, we shall study in this chapter. Even a healthy eye has its limitations, and many optical instruments have been devised to help it to see things too far away or too small for ordinary vision. And finally, there are many devices, such as cameras, stereopticons, and motion-picture machines, that enable us to see things far away from, or long after, their actual occurrence. All these devices for enabling us to see better, farther, or at a different time are called **optical instruments.**

In all of them we find **lenses**, and in some of them also **prisms.** To understand how optical instruments work, we must first study the passage of light through lenses and prisms; that is, the **refraction of light.**

448. Refraction in water. When a stick stands obliquely in water, it appears to be broken at the surface of the water

in such a way that the part under water seems to be bent upward (Fig. 508). The bottom of a tank of water always appears to be nearer the surface than it really is. A fish appears to be higher in the water than it actually is, so that if one wishes to spear it, one must aim *under* its image. All these phenomena are due to the **refraction** of the light as it passes from water into air. We have said that light advances in straight lines; but this is only true in a single substance. *In general, when light goes from one substance into another of different density, it is bent, or refracted, at the dividing surface.*

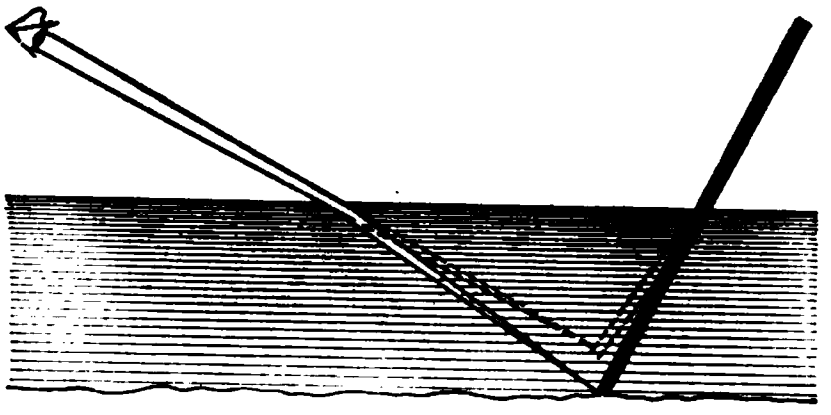


Fig. 508. A stick partly in water appears broken.

449. Law of refraction. To measure how much a beam of light is bent in passing from water into air, we may perform the following experiment.

We set a board vertically in a jar of water and fasten a wire (solder) with pins along the board (Fig. 509). If we fill the jar with water, and then look down along the wire, we see that the part under water appears to be bent upward. If we bend the part that is out of water until the whole wire seems to be straight, we have a model to show the path of the light in air and water. We may now remove the board from the water and draw the water line and the perpendicular (Fig. 510).

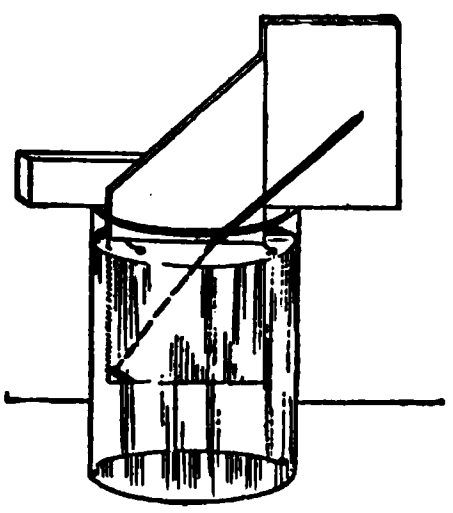


Fig. 509. Light is bent when leaving water obliquely.

From this experiment we see that a *beam of light in passing from water into air is bent away from the perpendicular.*

It might also be shown that a beam of light in passing from air into water, in the direction BO, is bent in the direction OA (Fig. 510). That is, a beam of light in passing from air into water is bent toward the perpendicular. In this case the line BO represents the **incident ray** and the line OA the **refracted ray.** The angle COB between the incident ray and the

normal is called the angle of incidence, and the angle AOD between the refracted ray and the normal is called the angle of refraction.

To show the relation between the angles of incidence and refraction, we lay off equal distances on the incident and refracted rays ($AO = BO$), and draw perpendiculars to the normal (AD and BC). We shall find that, whatever the angle of incidence, the line BC is always a definite number of times greater than AD. For example, in this case BC might be 4 inches, while AD might be 3 inches, and then the ratio BC/AD is $\frac{4}{3}$, or 1.33. This ratio is called the **index of refraction.** *Experiments show that this ratio is always the same for the same two substances, no matter what the angle of incidence may be.*

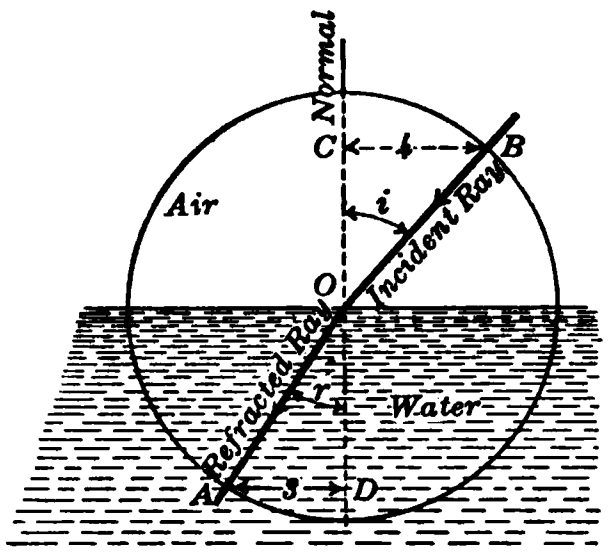


Fig. 510. Diagram of refraction of light passing from air into water obliquely.

This ratio may also be expressed in terms of the "sines" of the angles of incidence and refraction. *Sine* is the name used in trigonometry for the ratio of the opposite side to the hypotenuse; thus the sine of the angle of incidence i is BC/BO, and the sine of the angle of refraction r is AD/AO. Since $AO = BO$ by construction,

$$\frac{\text{sine of } \angle\, i}{\text{sine of } \angle\, r} = \frac{BC/BO}{AD/AO} = \frac{BC}{AD} = \text{index of refraction.}$$

450. Refraction of light by glass. We may also show that a beam of light is refracted in passing from air into glass.

Let a block of glass of semicircular shape be attached to an optical disk, as shown in figure 511. It will be seen that part of the ray is reflected by the glass as if it were a mirror, and part is refracted toward the perpendicular as it passes into the glass. It will also be seen that the angle of incidence is equal to the angle of reflection, but is greater than the angle of refraction. We may measure the perpendicular distances to the normal from the ends of the incident and refracted rays as seen on the disk, and compute the index of refraction for glass and air.

Ordinary crown glass bends a ray of light less — that is, has a smaller index of refraction — than glass made with lead, known as flint glass. The lead glass, which is denser, has an index of refraction with respect to air of about 1.7; while that of crown glass and air is about 1.5.

In general, light is bent in passing obliquely from one substance into another as from air to glass, diamond to air, or even from vacuum to air or from a layer of air of one density to one of another. Thus light is refracted in passing through the rising column of warm air over a stove, and things seem to shimmer or dance about.

Fig. 511. **Ray partly reflected and partly refracted by glass.**

The general rule is that when light enters a denser substance obliquely, it is bent toward the perpendicular.

451. Refraction of sunlight. An interesting case of refraction of light occurs in the atmosphere surrounding the earth. The air extends only a few miles above the surface of the earth, thinning out as it goes, and beyond is empty space. So when a ray of sunlight, *SO* in figure 512, comes through the air obliquely, it is bent gradually toward the normal in passing from one layer to another; the result is that the eye at *O* sees the sun in the direction *OS'*, instead of in its real position. For this reason the heavenly bodies rise somewhat earlier and set somewhat later than they would if this were not the case. This makes the day some 7 or 8 minutes longer.

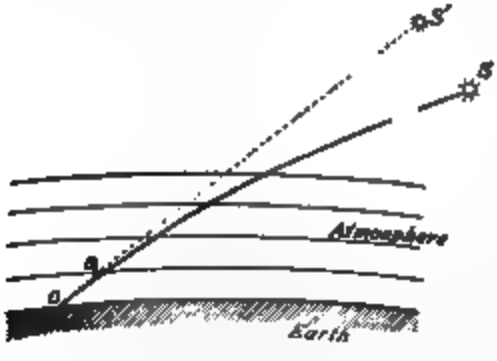


Fig. 512. **Refraction by the earth's atmosphere.**

452. Speed of light through space. The reason for the refraction of light was not understood until the velocity of light in different substances had been determined. Indeed, up to 1675 it was believed that light traveled instantaneously; that is, that light consumed no time in its passage between two points. About that time Roemer, a young Danish astronomer at the Paris Observatory, was observing the

moons of Jupiter. With great precision he observed just when one of the satellites *M* (Fig. 513) passed into the shadow cast by Jupiter *J*. The beginnings of these successive eclipses of Jupiter's satellite may be thought of as signals flashed at equal intervals. When the earth is traveling *away* from Jupiter, the observed interval between signals is greater than the true interval, because the light from each succeeding signal has a greater distance to travel to reach the earth. But when we are traveling *toward* Jupiter, the observed interval between signals is less than the true interval, because the light from each succeeding signal has a shorter distance to travel to reach the earth. Thus while the earth is traveling from *A* to *B*, the observed times of the eclipses are delayed more and more, and when the earth has reached *B*, the total delay has amounted to 16 minutes and 36 seconds (about 1000 seconds).

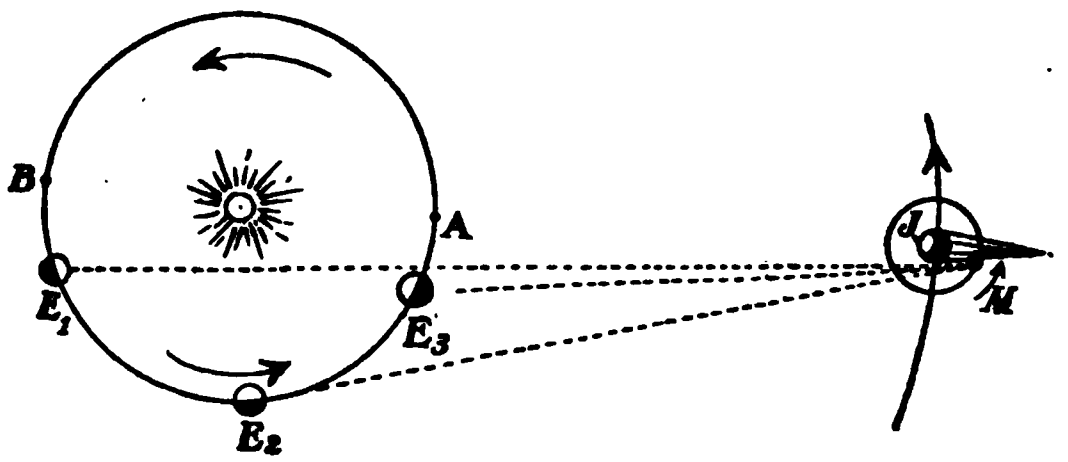


Fig. 513. Illustrating Roemer's way of measuring speed of light.

This means that it takes about 1000 seconds for the light to travel across the earth's orbit, a distance of 186,000,000 miles. Therefore the velocity of light is **186,000 miles per second** (300,000 kilometers per second). In recent years the velocity of light has been directly measured with great precision on the earth's surface by several methods, and the results agree very closely with those obtained so long ago by Roemer.

This velocity is so enormous that it is not strange that the earlier experimenters could not determine it. In fact, it takes only 0.001 of a second for light to travel as far as one can see on the earth. Light travels a very little more slowly in air than in a vacuum. In denser substances, such as water and glass, light travels much more slowly.

453. Light waves. Just as we think of sound as transmitted from a source through the air by a series of waves, so we think of light as transmitted through space by a series of **ether waves.** When the light comes from a point source, the spherical crest, or **wave front**, of each wave, spreads in all directions with equal velocity, and the direction of advance, being radial, is at

right angles to the wave front. Such a series of expanding waves is shown in figure 514(*a*), in which the curved lines are the wave fronts and the lines of arrows indicate the direction of advance of small sections of the wave front. These lines of advance are what were called **rays** in the last chapter. A bundle of rays is a **beam.** In a "parallel beam" (Fig. 514(*b*)) the wave fronts are plane and the rays are parallel.

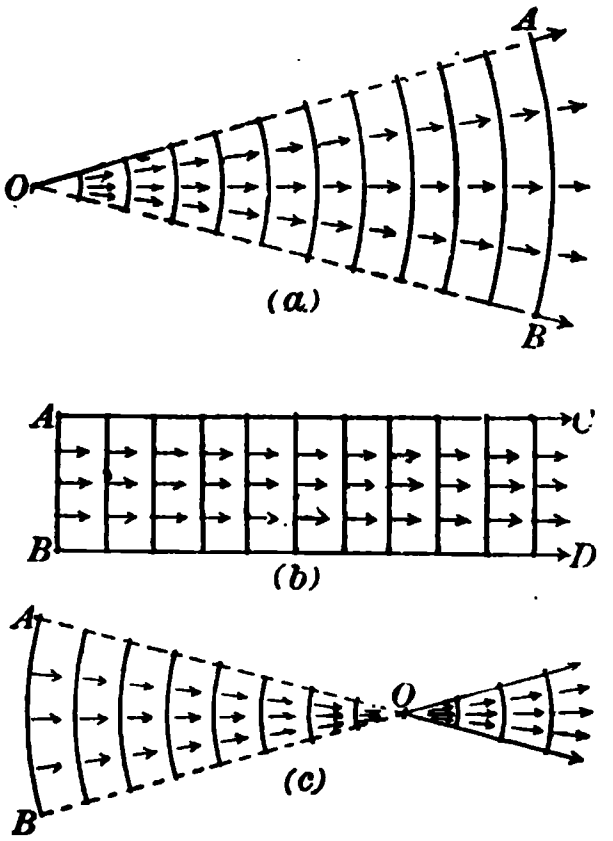


Fig. 514. Wave fronts.

By means of a lens or curved mirror, a beam of light may be made to converge toward a point, called the focus. In this case the wave fronts are concave spherical surfaces which contract as they approach the focus (Fig. 514(*c*)).

454. Why light is refracted. When a beam of light passes from air into water, there is a change in its velocity. To show how this causes a refraction of the beam, let the parallel lines in figure 515 represent wave fronts advancing in the direction of the arrows. As soon as the edge *B* of a wave front enters the water, it begins to advance slowly, while the part *A*, which is still in the air, advances with the same speed as before. Consequently the direction of the wave front is changed into the position *CD*, and the beam is bent into a direction nearer the perpendicular *PR*.

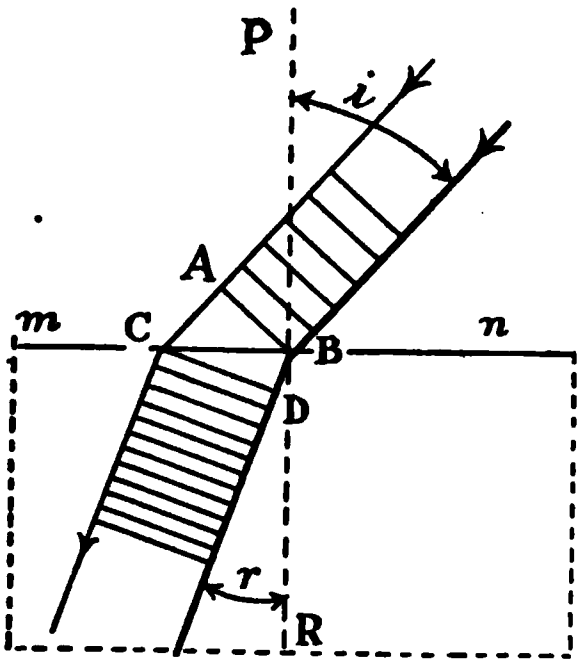


Fig. 515. Diagram to show cause of refraction.

This is somewhat analogous to a column of soldiers marching from a smooth, hard field into a rough, plowed field, where they are slowed

up. The man at B hits the rough ground before the man at A does, and so, while A travels the distance AC, B has gone a shorter distance BD. The result is that if B cannot hurry, and if A does not slow up, the column swings around from its original direction into one nearer the perpendicular PR.

When a beam of light enters water *perpendicular to the surface*, it suffers no refraction. The change in velocity is, of course, just the same whether the light enters normally to the surface or obliquely; but bending, or refraction, occurs only when the light enters obliquely.

455. Speed of light and index of refraction. From figure 515 it will be seen that the amount which the beam of light is refracted when passing from air into water depends upon the relation between the distances AC and BD; that is, upon the relation between the speed of light in air and its speed in water. Although it is not easy to measure the speed of light in water, yet it has been done. The speed in water has been proved to be about three fourths that in air. This means that the speed of light in air is 1.33 times the speed in water, which is the same number that we found from the index of refraction of water and air. In general

$$\textbf{Index of refraction} = \frac{\textbf{speed in air}}{\textbf{speed in other substance}}.$$

We may prove this as follows:

$$\text{Index of refraction} = \frac{\sin i}{\sin r} \text{ (see section 449).}$$

But i is equal to the angle ABC (Fig. 515), and $\sin ABC = AC/BC$; also r is equal to the angle BCD, and $\sin BCD = BD/BC$.

Therefore,

$$\frac{\sin i}{\sin r} = \frac{AC/BC}{BD/BC} = \frac{AC}{BD} = \frac{\text{speed in air}}{\text{speed in water}} = \text{index of refraction.}$$

456. Total reflection. We have seen in section 448 that when a beam of light passes obliquely from water or glass into air, the refracted ray is bent away from the perpendicular.

For example, in figure 516 the light coming from a point *O* under water, in the direction *oa*, is refracted in the direction *aa'*; the ray *ob* is refracted along *bb'* and *oc* is refracted along *cc'*. As the angle in the water increases, we come finally to a ray *od* which is refracted along *dd'*, and just grazes the surface of the water. The angle which is formed between the ray *od* and the normal *NM* is called the critical angle. For water and air it is about 49°. If this angle is exceeded, as in the case of the ray *oe*, the ray cannot leave the water at all, but is totally reflected at *e*, just as if it had fallen on a polished metal surface, and takes the direction *ee'*.

Fig. 516. Critical angle and total reflection of light by water

The critical angle is the angle in the denser medium which must not be exceeded if the ray is to get out.

To illustrate total reflection, we may hold a tumbler containing water and a spoon above the eye, and look up at the surface of the water. A very bright image of the part of the spoon in the water will be seen by total reflection.

If the apparatus shown in figure 517 is available, the paths of various refracted and reflected rays, including some that are totally reflected, can be studied with great ease.

Fig. 517. Apparatus showing refraction and reflection of light by water in a tank.

457. A prism as a mirror. In optical instruments it is frequently necessary to have a very perfect reflector, and for this purpose a right-angle prism with polished sides is used. Let a ray of light *AB* strike

the side XZ of such a prism (Fig. 518) at right angles. It suffers no refraction, but passes on through the glass to B on the side YZ, where it makes an angle of 45° with the normal mn. But the critical angle for crown glass is about 42°; therefore the ray AB does not emerge from the glass, but is totally reflected in the direction BC. It then strikes the face XY perpendicularly and emerges without refraction. The result is that the ray is bent 90°, as if there had been a plane mirror at YZ.

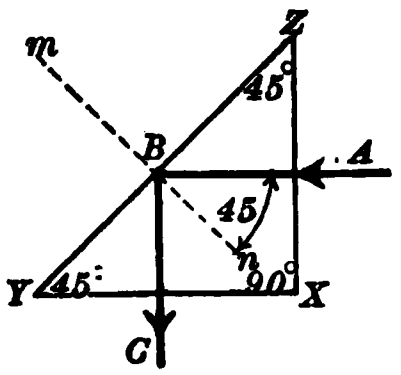


Fig. 518. Total reflection of light by a right-angle prism.

458. Refraction by plate with parallel sides. When a ray of light (AB in figure 519) passes through a glass plate with parallel faces, such as a good window pane, it is refracted at B *toward* the normal BN, and at C *away* from the normal CM. The result is that the ray CD is parallel to the ray AB. Consequently when we look at any object through a glass plate, we see it slightly displaced in position, but otherwise unchanged. When the plate is thin, this change of position is too slight to attract attention.

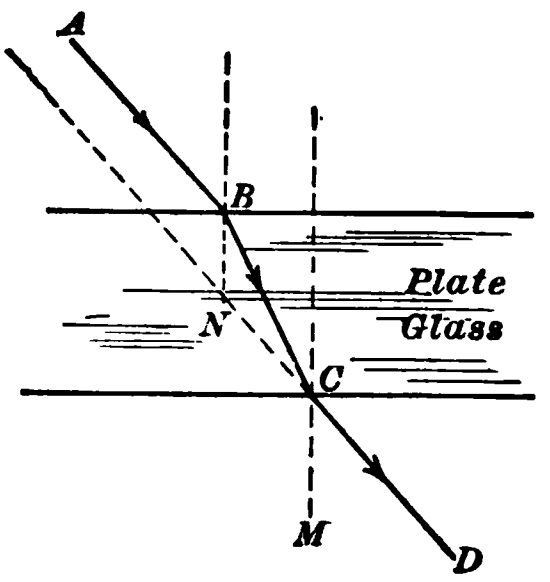


Fig. 519. Path of ray through plate glass.

459. Refraction by a prism. When a ray XY enters one side of a prism ABC as shown in figure 520, it is bent in the direction YZ; and on emerging, it is again bent in the direction ZW. Thus the ray XO is bent out of its original course to $X'W$. The total change of direction is measured by the angle XOX', called the **angle of deviation**. Any substance which has two plane refracting surfaces inclined to each other is a **prism**. The angle A is called the **refracting angle** of the prism.

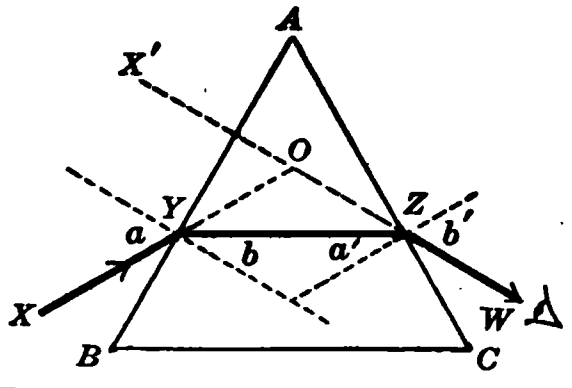


Fig. 520. Refraction of light by a prism.

The path of a ray of light through a prism can be found by drawing a diagram, like figure 510, at Y and again at Z. It should be remembered that *the beam is always bent toward the thicker part of a prism.*

QUESTIONS AND PROBLEMS

(The student should have a small protractor.)

1. In what direction must a fish look to see the setting sun?

2. Explain with a diagram how atmospheric refraction increases the length of daylight.

3. If the angle of incidence of a ray of light passing from air into glass is 68°, and the angle of refraction is 36°, find by construction the index of refraction.

4. If the index of refraction for air and water is 1.33, and the larger angle is 60°, find by construction the smaller angle.

5. Taking the index of refraction as 1.33, find by construction the critical angle for water.

6. If the critical angle for crown glass is 42°, find by construction the index of refraction.

7. Assuming the velocity of light in air to be about 186,000 miles per second and the index of refraction of flint glass to be 1.6, compute the velocity of light in flint glass.

8. The angles of a prism are 20°, 70°, and 90°. A ray of light enters normally the face bounded by the angles 90° and 70°. The glass has a critical angle of 42°. Prove that the ray will be twice reflected before it leaves the prism.

9. Will a beam of light going from water into crown glass be bent toward or away from the perpendicular?

10. Experiments show that when light passes from air into water, it is bent less than when it passes from air into carbon bisulfide at the same angle of incidence. Is the speed of light in carbon bisulfide greater or less than in water?

LENSES

460. Lenses, convergent and divergent. A lens is a piece of glass, or other transparent substance, with polished spherical surfaces. A straight line drawn through the centers C_1 and C_2 (Fig. 521) of the two spherical surfaces is called the **principal axis** of the lens.

Lenses are divided into two classes, converging or "thin-

edged" lenses (Fig. 521), and diverging or "thick-edged" lenses (Fig. 522). A converging lens is thinner at the edge than in the center. A common type of this class is the double convex lens. A diverging lens is thicker at the edge than at the center. The double concave lens is a common lens of this class. It should be remembered that *when a ray of light passes through a lens, it is always bent,* just as in a prism, *toward the thicker part of the lens.*

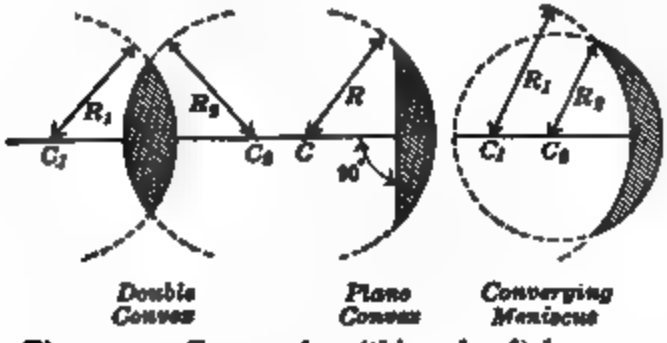


Fig. 521. Converging (thin-edged) lenses.

461. Action of a convex lens. If we hold a double convex lens so that the sunlight (or some other source of parallel rays) comes to it along its principal axis, we find that the light is refracted so as to converge nearly at one point. If a piece of paper is held at this point, a small but very bright image of the sun is formed and the paper is quickly charred. The thicker the lens, the nearer is this point, called the focus, to the lens.

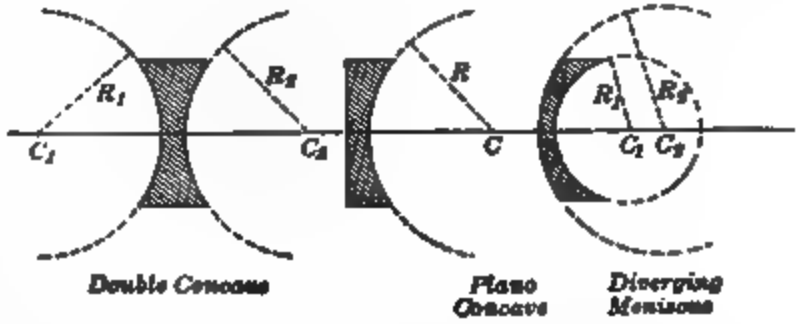


Fig. 522. Diverging (thick-edged) lenses.

The optical disk may be used here to show the action of a convex lens on parallel rays (Fig. 523).

The point where rays parallel to the principal axis converge is called the ***principal focus*** *of a lens.* A lens has a principal focus on each side, and the two are equidistant from the lens. *The distance from the lens to either principal focus is called the* ***focal length*** *of the lens.*

Fig. 523. Optical disk used to show action of converging lens.

Since an incident ray and its corresponding refracted ray are *reversible*, it follows that a light, placed at the principal focus, would send its rays through the lens in such a way as to come out parallel.

For an ordinary double convex lens with its two surfaces of the same curvature and made of glass whose index of refraction is about 1.5, the focal length is equal to the radius of curvature. If one surface is plane, the focal length is double the radius of curvature.

462. Change of wave front produced by a convex lens. We have already learned that light travels more slowly in glass than in air (section 455). The light waves from the sun or a distant object are practically *plane waves* when they strike the lens. The successive positions and shapes of the advancing waves are shown in figure 524 by lines drawn across the beam. It will be seen that the central portion of these waves is retarded more than the outer portions in passing through the lens. Therefore the light waves on emerging from the lens have a concave front. As light waves move at right angles to the front of the wave, the light is brought to a focus; but after passing the focus the waves have a convex front.

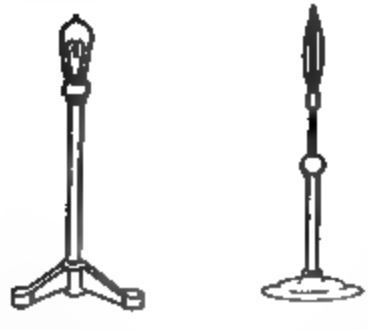


Fig. 524 Action of a converging lens on a plane wave front.

Fig. 525. Formation of an image on a screen by a convex lens.

463. Formation of images by lenses. If we place a luminous object, such as an electric lamp, near a convex lens but *beyond its principal focus*, the light rays from the object will be brought to a focus on the other side of the lens, and the image of the lamp may be clearly seen upon a screen placed at this point (Fig. 525). It will be noticed that the image is inverted

and larger than the object. If we interchange the position of the object (lamp) and the image (screen), or do what amounts to the same thing, interchange the *object-distance* and *image-distance* by moving the lens nearer the screen, we find another position of the lens which gives a clear inverted image but one smaller than the object. We may move the screen farther away from the lamp and again find two positions for the lens which give sharp, distinct images.

Two points so situated on opposite sides of a lens that an object at one will form an image at the other are called ***conjugate foci.***

464. Equation for convex lenses. The relative positions of an object and its image formed by a convex lens are determined by the focal length of the lens. The relation between the distance of the object from the lens, the distance of its image from the lens, and the focal length (when the lens is thin) is given by the same equation as for mirrors (section 446) :

$$\frac{1}{D_o} + \frac{1}{D_I} = \frac{1}{f}$$

where D_o = distance of object from lens,
D_I = distance of image from lens,
f = focal length of lens.

465. Discussion of the lens formula. If the object is so far away that the rays from any point of it to different parts of the lens are practically parallel, the image is formed at F; for D_o is very large, and so $\frac{1}{D_o}$ is nearly zero; this leads to $D_I = f$ (Fig. 526).

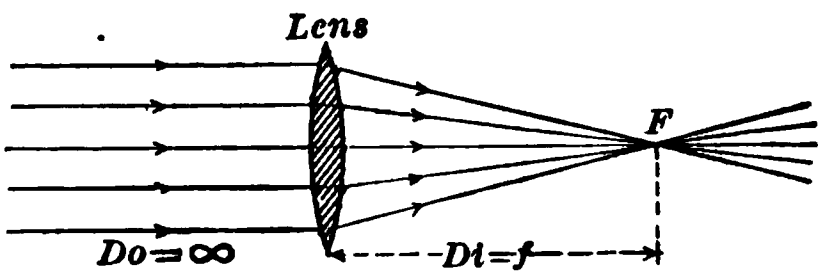


Fig. 526. Image of distant object is at F.

If the object is brought nearer the lens, the image moves farther away from the lens. When $D_o = 2f$, $D_I = 2f$ also, as shown in figure 527.

If the object is brought still nearer the lens, the image moves still

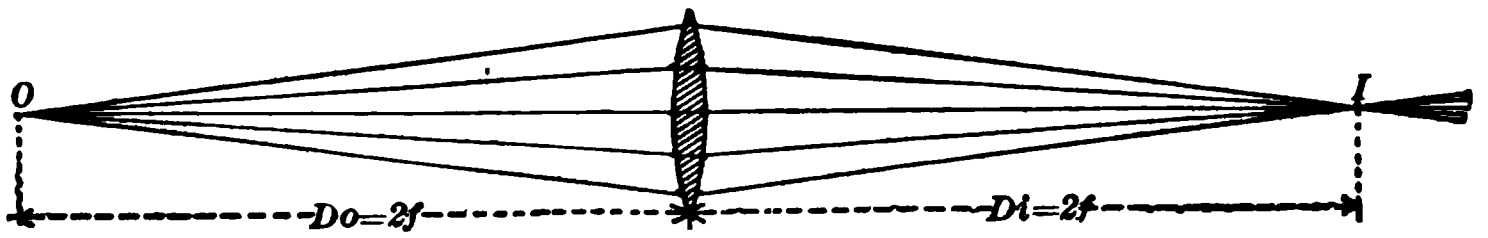


Fig. 527. Image at same distance as object.

farther away from the lens, until, when the object is at the principal focus F, the distance of the image becomes infinitely great, and the rays that go out from the lens are parallel (Fig. 528).

If the object is brought even nearer the lens (inside the principal focus), the rays on the farther side diverge as if they came from a focus I be-

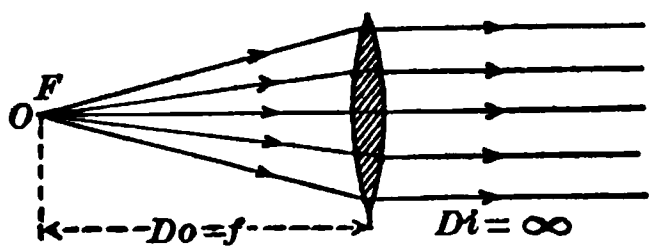


Fig. 528. Object at F, rays parallel.

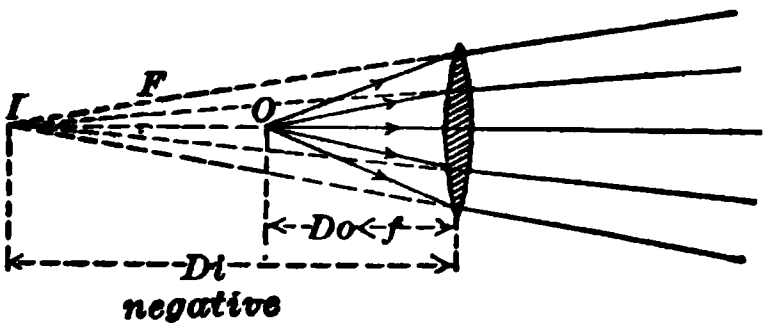


Fig. 529. Object inside F, image virtual.

hind the lens (Fig. 529). In this case, D_I in the formula is **negative.** This means that the image is **behind** the lens, that is, on the same side of the lens as the object.

466. Construction of images formed by lenses. The geometrical construction of images formed by lenses will indicate the size and position of these images. The method of procedure is the same as that used for spherical mirrors (section 441). If we trace two rays from any point of the object to their intersection, we have the position of the corresponding point of the image. For example, in figure 530, a ray from A parallel to the principal axis must, after refraction by the lens, pass through the principal focus F. Another ray from A, passing through the center of the lens, is undeviated. The point A' where these rays meet is the image point of A. Then from similar triangles it is readily seen that

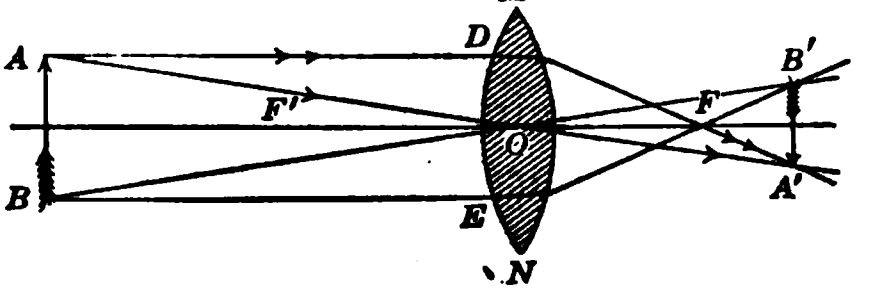


Fig. 530. Size of real image.

$$\frac{\text{Length of image}}{\text{Length of object}} = \frac{\text{distance of image from lens}}{\text{distance of object from lens}}.$$

The ratio of the length of the image to the length of the object is called the linear magnification.

In figure 530 the object AB is **beyond the principal focus** of the **convex** lens, and the image $A'B'$ is **inverted, real,** and, in this case, smaller than the object.

In figure 531 the object *AB* is between the principal focus *F* and the lens. The image *A'B'* is erect, virtual, and larger, and can be seen only by looking through the lens. A virtual image cannot be projected upon a screen as a real image can.

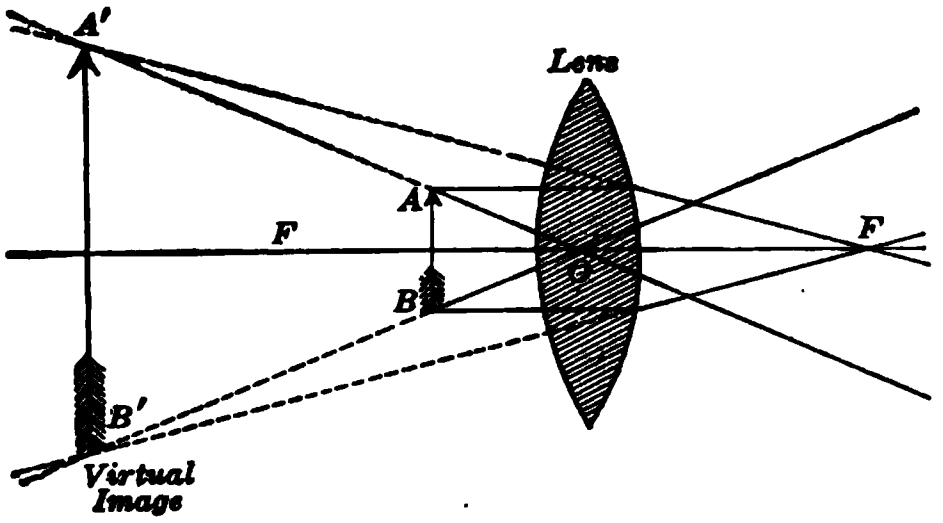


Fig. 531. Size of virtual image.

467. Image in a concave lens. When a series of rays parallel to the principal axis pass through a concave lens, they emerge as divergent rays and appear to be coming from the point which is called a **virtual focus.**

We may demonstrate this divergent action of a concave lens by means of an optical disk, as shown in figure 532.

To explain this phenomenon, we have only to imagine a series of plane waves striking a concave lens. Since it is thinner at the center than at the edges, the middle of the wave is retarded less by the glass than its ends. The emergent wave front is convex and forms a diverging cone of light which proceeds as if coming from the virtual focus.

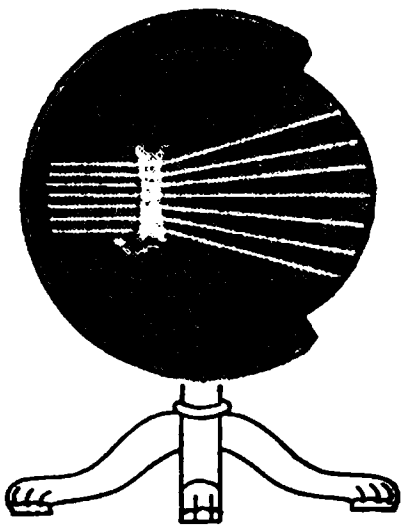


Fig. 532. Optical disk used to show action of a diverging lens.

Figure 533 shows the geometrical method of constructing and locating the image in a concave lens. It will be seen that the image is apparently on the same side of the lens as the object, and is **virtual, erect, and smaller** than the object. In applying the lens equation to concave lenses, the focal length is considered negative; therefore a concave lens is often called a **minus (−) lens**, while a convex lens is a **plus (+) lens.**

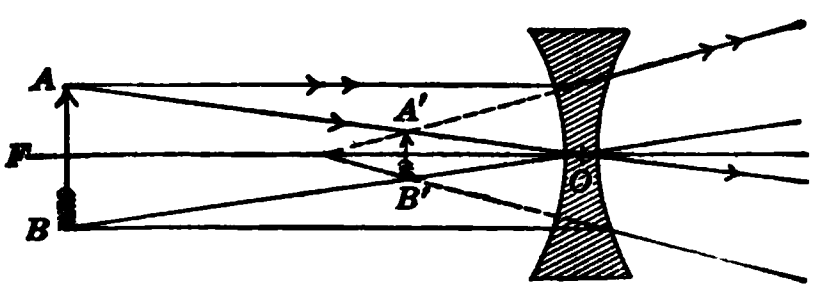


Fig. 533. Virtual image formed by a concave lens.

468. Defects of images formed by lenses. In the construction of figure 530 it is assumed that all the rays coming from a point in the object are accurately refracted by the lens to one point. But as a matter of fact the rays that strike the outer portions of a lens are refracted more than the rays which fall on the central portion of the lens, and so come to a focus nearer to the lens. This is called **spherical aberration.**

This may easily be demonstrated by forming the image of an electric arc on a distant screen by means of the condensing lenses of an ordinary projecting lantern (section 474). The image will be blurred. But if the lens is covered except for the central portion, the image will be sharp. Try the effect of covering the lens except for a narrow circular zone equally distant from the center. How must the lens be moved to give a sharp image when the zone is used?

The effects of spherical aberration are to make the image indistinct and to distort its shape. If the outer rays are cut out by means of a **diaphragm**, or **stop**, the sharpness of the image is improved, but at the same time its brightness is diminished. In large lenses, such as those used in telescopes, the outer portions are so ground that their refracting power is diminished by the proper amount to insure distinct images.

This whole geometrical theory of lenses applies to only very thin lenses, and to cases where the light may be assumed to pass through the lens in a direction not greatly inclined to the axis of the lens. In practice, combinations of lenses are nearly always used instead of simple lenses, and these combinations are designed so that the imperfections of one lens are compensated for or balanced by the imperfections of another lens.

QUESTIONS AND PROBLEMS

1. A convex lens has a focal length of 16 centimeters. Find the position and nature of the images formed when objects are placed 10 meters, 50 centimeters, and 10 centimeters respectively from the lens.

2. If an object is placed 32 centimeters from the lens described in problem 1, how far is the image from the lens?

3. A lamp placed 60 centimeters from a lens forms a distinct

image on a screen 20 centimeters away on the other side. Find the focal length of the lens.

4. A double convex lens used as a reading glass has a focal length of 15 inches and is held 10 inches from the book. What is the distance of the image from the lens?

5. What is the ratio of the length of the image formed in problem 4 to the length of the object?

6. Is it true for both mirrors and lenses that *real images are always inverted?*

7. A small object moves along the principal axis of a convex lens toward the lens. Describe the changes in the position and size of the image. Is the image real or virtual?

8. At what distance from a convex lens must an object be placed in order that the image may be half as long as the object? Focal length of lens is 30 centimeters.

9. At what distance from a convex lens must an object be placed in order that the image may be twice as long as the object? Focal length of lens is 24 centimeters.

10. An object is 30 centimeters from a lens, and its image is 3 centimeters from the lens on the same side. Is the lens convex or concave? What is its focal length?

Optical Instruments

469. Photographic camera. A camera is merely a light-tight box (Fig. 534) with a **converging lens** at one end, so mounted as to form an image of an outside object upon a "**sensitized**" **plate** or **film** at the other end. This plate consists of a silver compound spread on a glass plate or celluloid sheet (film). The light is allowed to pass through the lens for a time which varies from a thousandth of a second up to several minutes, according to the lens, the brightness of the object to be photographed, and

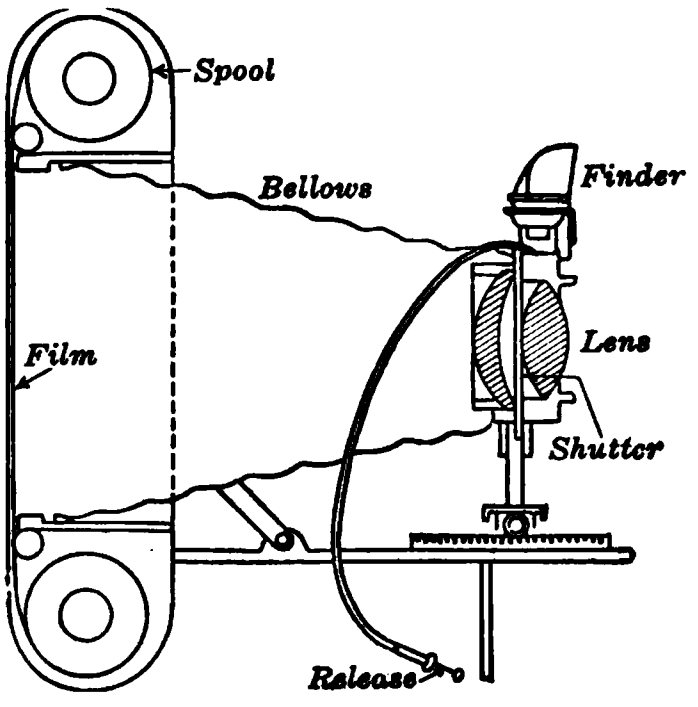


Fig. 534. A folding pocket camera.

the "speed" of the sensitized plate. The image on the plate is not visible until the plate is placed in a mixture of chemicals called a developer.

To obviate the spherical aberration of a single lens, a **diaphragm** is put in front of the lens in order to limit the size of the pencil of light. With a small opening, or stop, we get great sharpness in the picture, but must expose it for a longer time. A "combination lens," with the diaphragm between the two lenses, is used to take clear pictures of rapidly moving objects. Since the plate on which the image is formed must be in the position which is the conjugate focus of the position occupied by the object, the camera is usually made with a bellows so that it can be "focused" on objects at varying distances.

470. The eye. The human **eye** (Fig. 535) is essentially a little camera, with a lens system in front, and a sensitive film, made of nerve fibers, at the back.

It has the great advantage over any other camera in that it can take a continual succession of pictures all on the same film, "developing" them instantaneously by some unknown chemical or electrical process in the nerve fibers, and transmitting the results equally instantaneously over a "private wire" (the optic nerve) to "headquarters" (the brain).

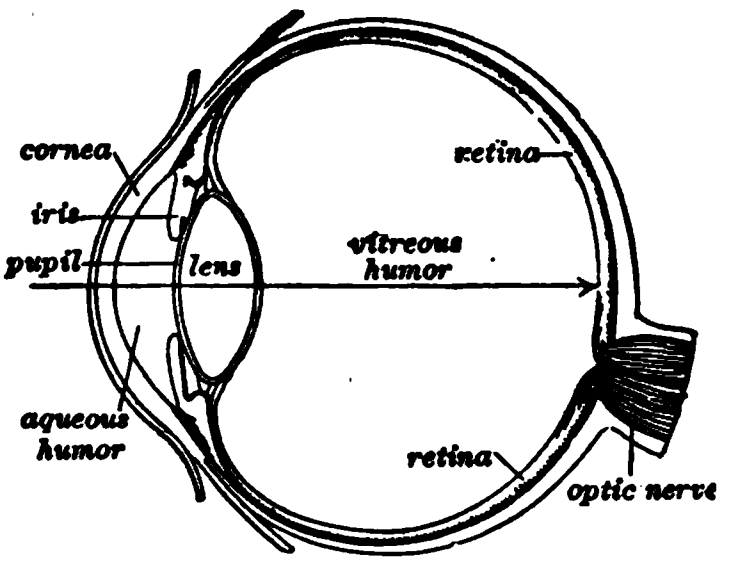


Fig. 535. Section of the human eye.

The structure of the eye is shown in figure 535. There is an outer horny membrane, the **cornea**, holding a watery fluid called the **aqueous humor.** There are also an adjustable diaphragm, or stop, called the **iris**, and a **crystalline lens.** The latter has a somewhat higher index of refraction than either the aqueous humor in front or a similar fluid, **the vitreous humor**, behind. At the back is the nerve layer, or **retina**, which acts as the sensitized film.

It should be noticed that most of the converging power of the eye comes, not in the lens, but at the front surface of the cornea. This explains why we can never see objects distinctly when swimming under water. The aqueous fluid and the water outside are so much alike that there is no longer any refraction of the light as it strikes the cornea; and the lens by itself is not powerful enough to bring the light to a sharp focus on the retina.

471. Focusing the eye. If an object is moved nearer a camera, the distance between the plate and lens must be increased; or else a lens of greater convexity, that is, of shorter focus, must be substituted, if the picture is to be sharp. Of these two possibilities, the eye chooses the second. It adapts itself to varying distances, not by moving the retina, but by changing the focal length of the lens. When the muscles of the eye are relaxed, the lens is usually of such a shape as to focus clearly on the retina objects which are at a considerable distance. When one wishes to look at near objects, a ring of muscle around the crystalline lens causes the lens to become more convex, so as to form a distinct image on the retina. This power of adjustment of the lens of the eye for objects at different distances is called **accommodation.** It is often said that objects are seen most distinctly when held about 10 inches (25 centimeters) from the eye. This simply means that 10 inches is about as near as one can usually focus an object distinctly; and since the shortest distance gives the largest image, this is where we automatically hold an object when we want to see its details.

472. Imperfections of the eye. In the **short-sighted** eye the image of a distant object is formed in front of the retina (at *A* in figure

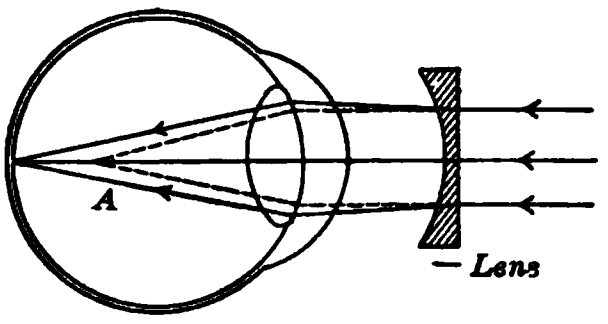


Fig. 536. A short-sighted eye.

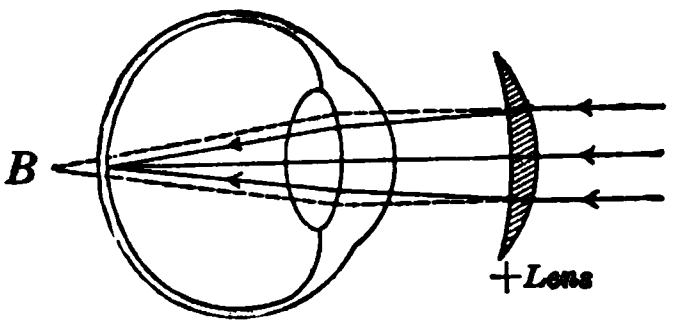


Fig. 537. A far-sighted eye.

536). This may be due to too great convexity in the crystalline lens, or to the oval shape of the eyeball. A person who is short-sighted must bring objects close to the eye to see them distinctly. Spectacles with **concave** lenses are used to correct **short-sighted** eyes.

In the **far-sighted** eye the image of an object at an ordinary distance would be formed behind the retina (at *B* in figure 537). This is because the crystalline lens is too flat, or the length of the eyeball is too

short. To see distinctly, such a person must hold objects at a distance. **Convex** lenses are used for **far-sighted** eyes. In old age the lens of the eye loses its power of accommodation and so requires a convex lens.

Another defect of the eye is **astigmatism**, which occurs when the lens of the eye or the cornea does not have a truly spherical surface. The effect is that a spot of light, like a star, is seen as a short, bright line. In a case of astigmatism all the lines in such a diagram as figure 538 will not appear equally distinct. Those in one direction will be sharply defined, while those at right angles to them will appear broadened and blurred. This defect is corrected by the use of **cylindrical** lenses.

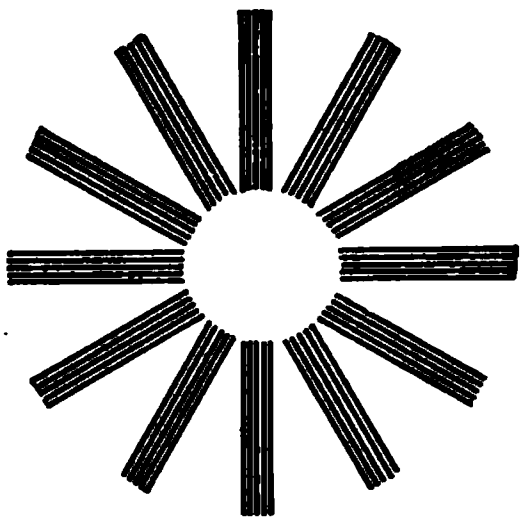


Fig. 538. Lines to test astigmatism.

473. Apparent distance and size. The apparent size of an object depends on the size of the image formed on the retina, and consequently on the **visual angle.**

From figure 539 it is evident that this angle increases as the object is brought nearer the eye. For example, when we look along a railroad track, the rails seem to come nearer together as their distance from us increases. The image of a man 100 yards away is one tenth as large as the image of the same man when he is 10 yards off. We do not actually interpret the larger image and larger visual angle as meaning a larger man, because by experience we have learned to take into account the known distance of an object in estimating its size.

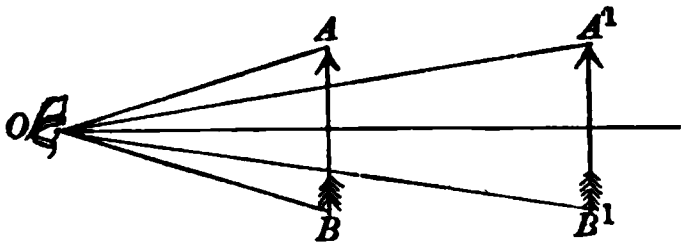


Fig. 539. The visual angle.

Distant objects seen in clear mountain air often seem nearer than they really are. That is because we see the objects more clearly and distinguish the details more sharply; and this often leads us to think that they are smaller than they really are. The moon, on the other hand, seems bigger when near the horizon than when high up in the sky, because we can compare it with objects whose size we know. It is only by long experience that we learn to estimate the actual size and distance of objects.

474. Projecting lantern. The projecting lantern, or **stereopticon**, is used to throw an image of a brilliantly illuminated object or picture upon a screen. It consists essentially of a

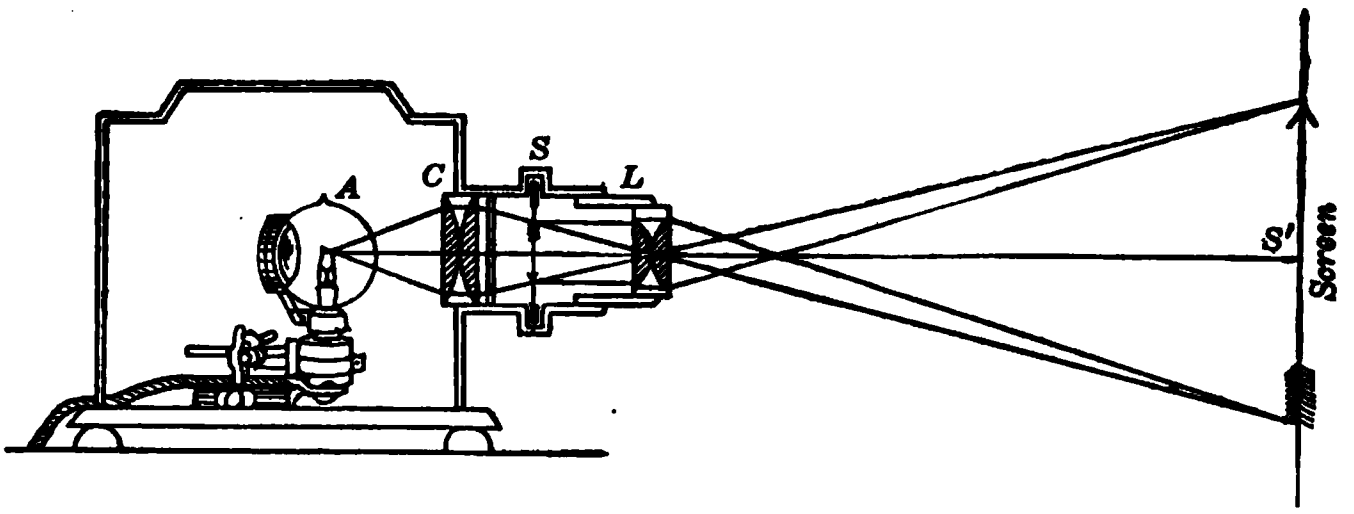


Fig. 540. A projecting lantern for slides.

powerful source of light, such as an electric lamp A (Fig. 540), two **condensing lenses** C, which converge the light through the slide, or transparent picture, S, and a combination front lens, or **objective**, L, which forms a real image of the picture on the screen S'. It will be noticed that the lantern is much like the camera except that the object and image have been interchanged. Since the screen is usually at a considerable distance, the slide S is only a little beyond the principal focus of the objective L. It is very important to have a powerful light source which is small in size. For this purpose an electric arc or an electric glow lamp, in which the filament is coiled into a small space, is generally used.

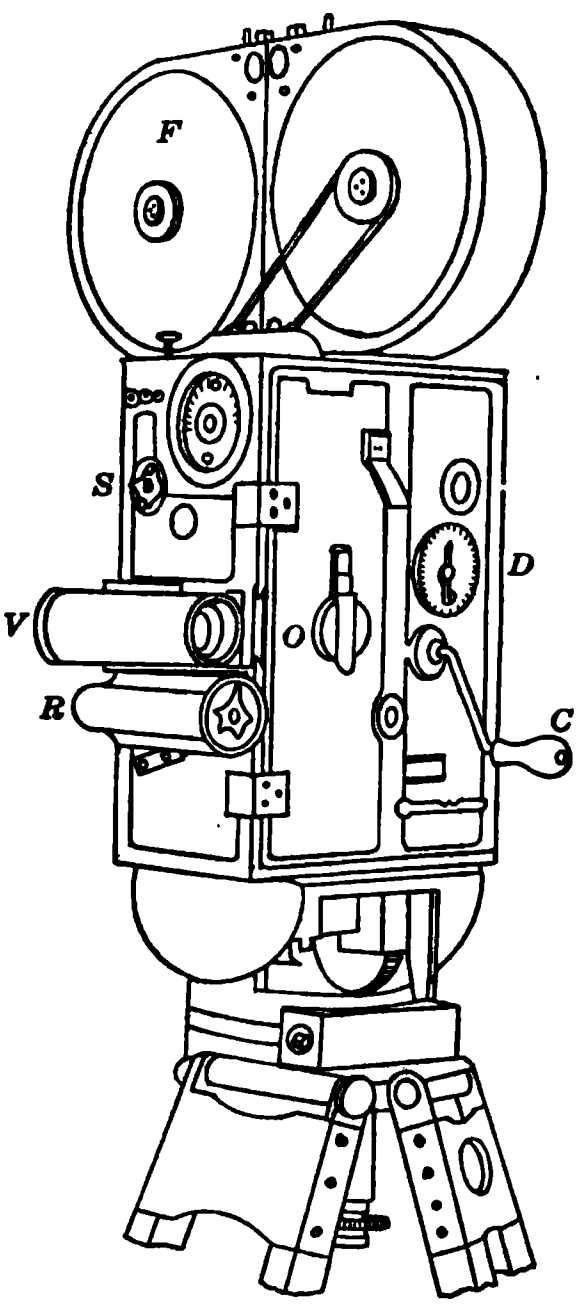


Fig. 541. A motion-picture camera.

475. Motion pictures. The motion-picture camera (Fig. 541) takes a series of pictures on a long narrow film. The camera is operated by a crank so that it opens and closes the shutter about 16 times a second. The film moves a little while the shutter is closed, but remains stationary while it is open. The pictures (Fig. 542) are about $\frac{3}{4}$ of an inch high

Fig. 542. A section of a motion-picture film, showing Tilden, the tennis player, in action.

and about 1 inch wide. The films are made up in reels of about 1000 feet each, and since about 1 foot of film moves past the lens every second, one reel of film contains about 16,000 pictures. Each picture of such a series differs slightly from the preceding one, if anything is

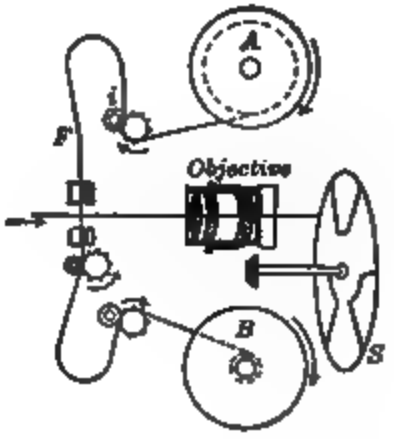


Fig. 543. A motion-picture projector with diagram of some essential parts.

moving in the field of the camera. From such a series of negatives any number of reels of positives may be printed for projection purposes. By means of a special type of projection lantern (Fig. 543) the series of positive pictures is thrown on the screen at the same rate of speed as that at which they were taken. The sensation produced by one picture remains until the next picture appears, so that we are not aware of any interruption between the pictures. Thus we see not *moving* pictures but a rapid succession of *stationary* pictures.

476. The simple microscope, or magnifying glass. We have said, in section 471, that the distance of most distinct vision is about 10 inches. If an object is placed at a greater distance than this, the image on the retina is smaller and the details of the object are not seen so distinctly. If the object is placed nearer than this, the image on the retina is blurred.

By placing the eye near a double convex lens, often called a **magnifying glass**, and placing the object to be examined on

the other side a little nearer the lens than the principal focus, we see a magnified, erect image, as shown in figure 544. The object-distance is adjusted until a clear image is formed; then the image-distance is usually about 10 inches. The magnifying power of a simple microscope is the ratio of the size of the image to the size of the object. This is equal to the distance of the image divided by the distance of the object, that is, $10/D_o$, D_o being the distance of the object (in inches) from the lens.

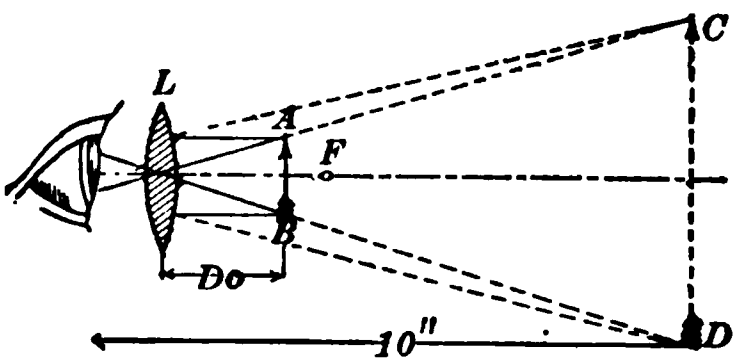


Fig. 544. Diagram of a magnifying glass.

Thus if for distinct vision a magnifying glass is held 1 inch from an insect, the magnification will be 10 diameters.

477. Compound microscope. Very small objects are made visible by the **compound microscope.** It consists of *two* lenses

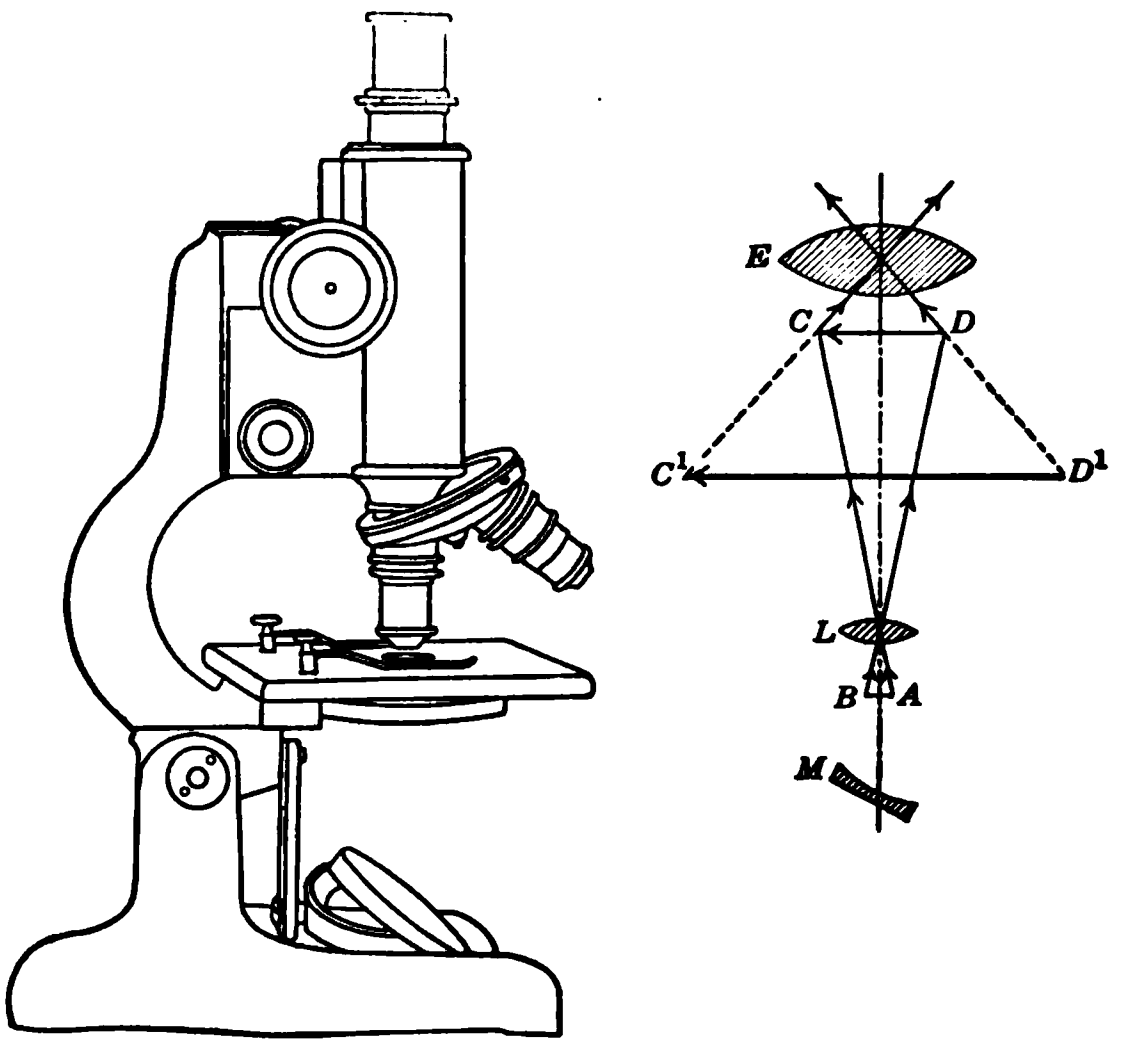


Fig. 545. A compound microscope, and a diagram of its optical parts.

or lens systems which are placed at the ends of a tube. The object AB is put just outside the principal focus of the smaller lens L (Fig. 545), called the **objective**, which forms an enlarged, real image CD. This real image is then examined through the **eyepiece** E, which acts like a magnifying glass, giving a still larger virtual image at $C'D'$, about 10 inches from the eye.

The image CD is magnified as many times as its distance from the lens L is greater than the focal length of that lens. Usually the distance of CD from L is about 150 millimeters; and so, if the lens has a focal length of 5 millimeters, the image CD is 30 times as long as the object AB. If the eyepiece still further magnifies the image 10 times, the magnifying power of the combination is 10×30, or 300 diameters. Microscopes magnifying as much as 2500 diameters are sometimes used.

We are indebted to the microscope for many valuable discoveries about the structure and life of plants and animals, about the smallest living things, and about the causes of disease.

478. The telescope. The telescope enables us to see objects so far away that we could not otherwise distinguish their de-

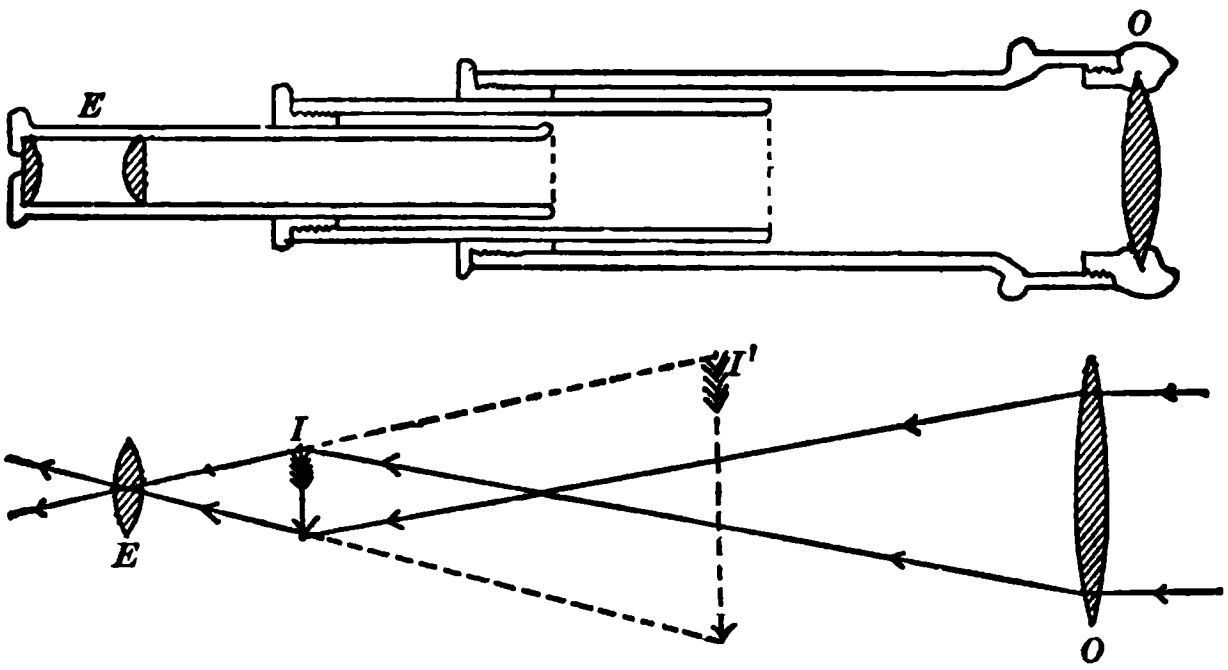


Fig. 546. Astronomical telescope and optical diagram.

tails. The simpler sort, called the **astronomical telescope,** (Fig. 546) consists of two lenses or lens systems, the large objective O and the eyepiece E. The inverted real image I, formed by the lens O, is much smaller than the object, but it is brought so near to the observer that it can be examined through

the eyepiece *E*, which acts like a magnifying glass. The two lenses are mounted in an extension tube so that the eyepiece can be drawn farther from the objective when objects near at hand are to be examined. Since the magnifying glass, or eyepiece, does not reinvert, the observer sees things upside down, just as he does in a microscope.

479. The erecting telescope, or spyglass. This instrument (Fig. 547) is like the astronomical telescope except that an additional converging lens or lens system *L* is introduced between the object glass *O* and the eyepiece *E*. This lens *L* inverts the image *I*, forming another

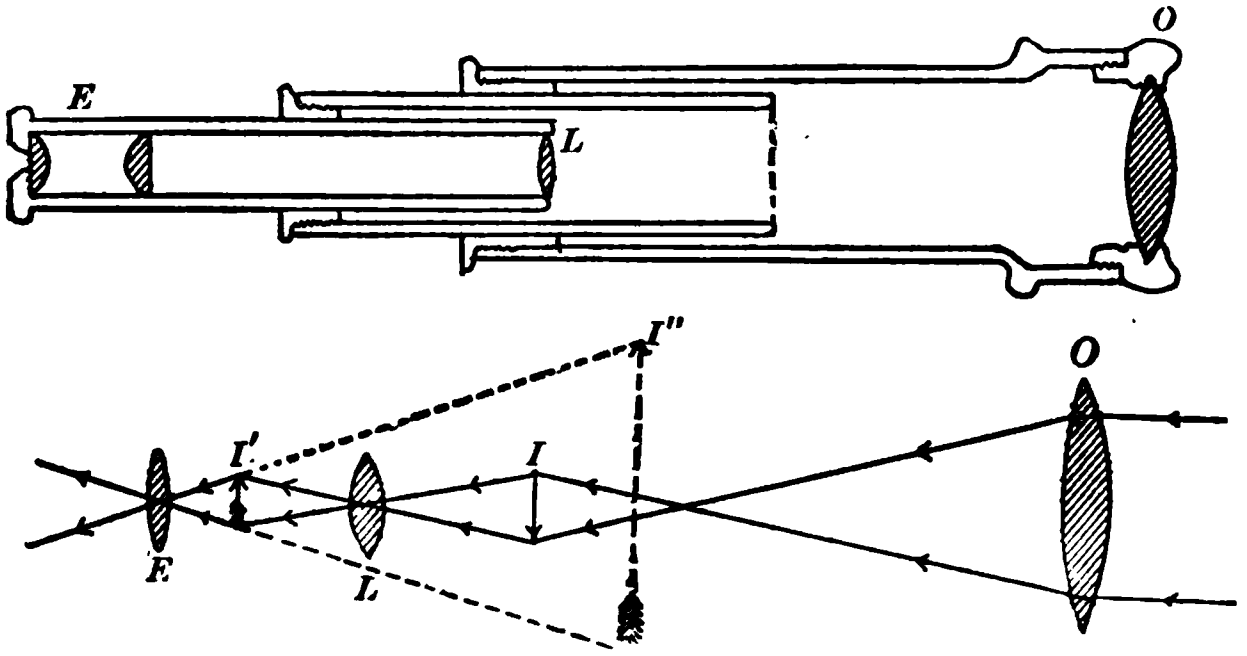


Fig. 547. Erecting telescope, or spyglass.

real image at *I'*; then this erect image *I'* is magnified by the eyepiece, which forms an enlarged, erect, virtual image *I''*. In the ordinary spyglass the eyepiece is a combination of two lenses, which act like a single magnifying glass. The introduction of the erecting lens *L* lengthens the telescope tube considerably.

Such telescopes are used in sighting long-range rifles. The "transit" and "level" used by surveyors consist of a telescope provided with cross-hairs stretched across the telescope tube in the plane where the image of a distant object is formed by the object glass.

480. The opera glass. The opera glass, shown in figure 548, is a telescope whose eyepiece is a diverging, or concave, lens. Since the eyepiece has approximately the same focal length as the eye of the observer, its effect is practically to neutralize the lens of the eye. So we may consider that the object glass forms its image directly on the retina. The field of view of the opera glass is small, and so it is

usually made to magnify only three or four times. But it has the advantage of being compact and giving an erect image. The distance between the two lenses is equal to the *difference* of their focal

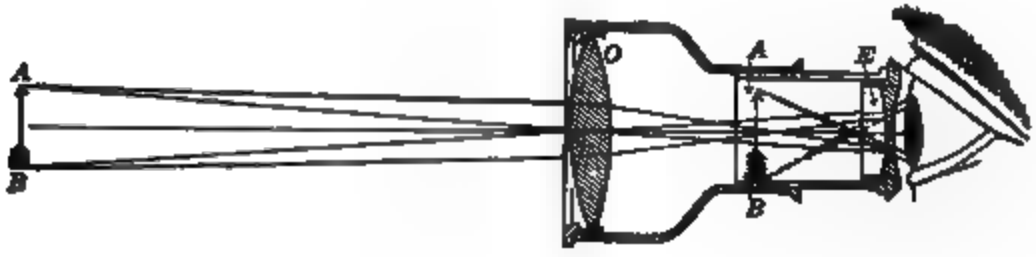


Fig. 548. Opera glass.

lengths. Galileo made a telescope on this plan which magnified about 30 diameters and enabled him to make some exceedingly important discoveries.

481. The prism field glass, or binocular. An instrument, called a binocular, has come into use in recent years which has the wide field of view of the spyglass and at the same time the compactness of the opera glass. Compactness is obtained by causing the light to pass back and forth between two reflecting prisms, as shown in figure 549. This device enables the focal length of the object glass to be three times as great as in the ordinary field glass for the same length of tube, and so the magnifying power is correspondingly increased.

Fig. 549. Prism binocular.

Furthermore, the reflections in the two prisms secure an erect image without the use of the erecting lens of the ordinary terrestrial telescope; for one double reflection tips the image right side up, and the other shifts right and left, thus restoring it completely to its natural position.

Questions and Problems

1. When a camera is focused on an automobile 100 yards away, the plate is 8 inches from the lens. How much must the distance between the lens and the plate be changed when the automobile is only 10 feet away? Must the distance be shortened or lengthened?

2. A 5-inch post card is to be projected on a screen 20 feet away from the objective, so that the picture will be 5 feet long. Find the focal length of the lens required.

3. A photographer with a 12-inch lens (*i.e.*, focal length = 10″) wants to make a full-length picture of a 6-foot man standing 10 feet from the lens. How near the lens must the plate be placed?

4. How long a plate must be used in problem 3?

5. How near to an object must a hand magnifier of 1.2 inches focal length be held to magnify it 6 diameters?

6. A magnifying glass of 3 centimeters focal length is held 2.7 centimeters from an object. (*a*) Where will the image be formed? (*b*) How much will it be magnified?

7. In a compound microscope the objective lens L (Fig. 545) has a focal length of one inch, and the object AB is 1.1 inches away. How far from the lens is the image CD? How many times is it magnified? If the eyepiece magnifies this image 20 times, what is the magnifying power of the instrument?

8. What is meant by a "fixed focus" camera, and how is such a camera constructed?

9. How does a wide-angle lens differ from a long-focus lens?

10. If the picture formed on a screen by a projection lantern is too small, which way must the lantern be moved in order to increase its size?

11. Spectacles are sometimes made with two sets of lenses (bifocal). What are the advantages and disadvantages of such lenses?

PRACTICAL EXERCISES

1. The periscope. The essential parts of one form of periscope are shown in figure 550. Explain the function of each part. Build a simplified periscope to demonstrate the principles involved.

2. Range finder. Find out how this instrument enables the observer to determine quickly the distance of an object. (Consult *Ferry's* General Physics — John Wiley and Sons.)

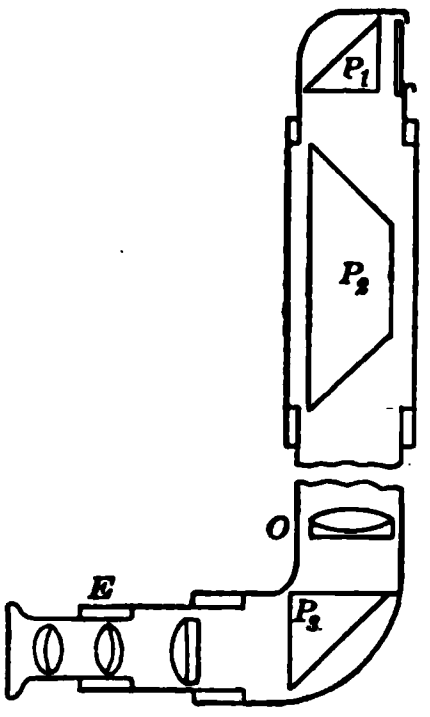


Fig. 550. Diagram of the essential parts of a periscope.

SUMMARY OF PRINCIPLES IN CHAPTER XXI

Refraction occurs when light passes obliquely from one transparent substance to another.

When light enters a *denser* substance obliquely, it is bent *toward* the perpendicular.

$$\text{Index of refraction} = \frac{\text{sine of angle of incidence}}{\text{sine of angle of refraction}} = \frac{\text{speed of light in air}}{\text{speed of light in other substance}}.$$

Velocity of light = 186,000 miles per second

$$= 3 \times 10^{10} \text{ centimeters per second.}$$

Critical angle is the angle in the denser medium which must not be exceeded if the ray is to get out.

Prism bends light toward thick edge.

Convex (thin-edged) lens converges light inward.

Concave (thick-edged) lens diverges light outward.

Principal focus is convergence point for rays parallel to axis.

Lens formula: holds for both converging and diverging lenses:

$$\frac{1}{\text{Object-distance}} + \frac{1}{\text{image-distance}} = \frac{1}{\text{focal length}}.$$

For *convex* lens, focal length is *positive*.

For *concave* lens, focal length is *negative*.

For *real* image, lens between image and object, image-distance is *positive*.

For *virtual* image, on same side of lens as object, image-distance is *negative*.

Size rule: Holds for both converging and diverging lenses:

$$\frac{\text{Length of image}}{\text{Length of object}} = \frac{\text{image-distance}}{\text{object-distance}}.$$

QUESTIONS

1. Which people would be more likely to be short-sighted, those who live much out of doors or those who stay much indoors?

2. How would you distinguish between a slightly concave and a slightly convex spectacle lens?

3. What are the defects of a pinhole camera?

4. What is the difference between a refracting and a reflecting telescope?

5. Prism glass is often used for the upper part of shop windows and doors and for windows facing on narrow courts. Draw a cross section of a plate of prism glass and explain its action.

6. Why is it necessary to build powerful telescopes very wide as well as very long?

7. Why is it best to have your light for writing or sewing come from over your left shoulder?

8. Explain how it happens that the wheels of moving vehicles in a motion picture sometimes seem to be rotating backwards.

9. What part do the condensing lenses play in the action of a stereopticon?

CHAPTER XXII

SPECTRA AND COLOR

Prism spectrum — achromatic lenses — spectroscope — types of spectra — spectrum analysis — Fraunhofer lines — wave length of light — colors of objects — colors of thin films — infra-red and ultra-violet — electromagnetic theory.

462. Analysis of light by prism. If we let a beam of sunlight (or one from an electric arc lamp) pass through a narrow slit into a dark room, and put a glass prism in its path (Fig. 551), the beam of light is refracted. If we put a white screen in the path of the refracted light, a band of colors is formed. In this band are red, orange, yellow, green, blue, and violet, which blend gradually into each other.

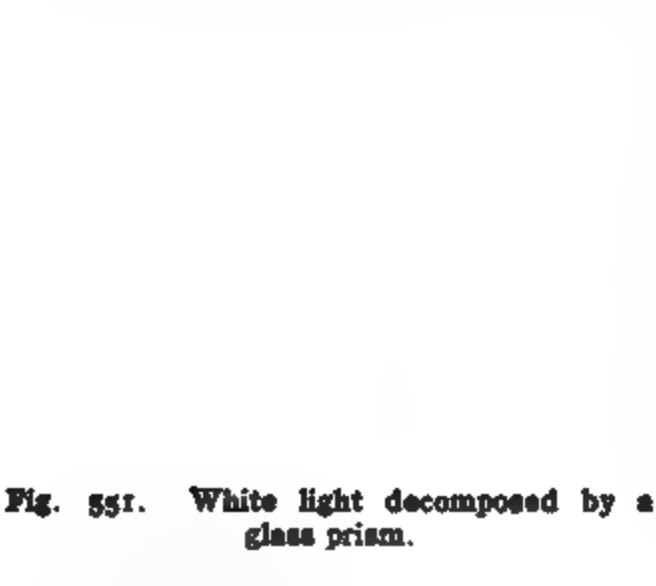


Fig. 551. White light decomposed by a glass prism.

A sharper image will be formed if a convex lens (focal length about 12 inches) is placed so as to focus the slit on the screen, and if the prism is placed near the principal focus on the screen side of the lens.

The colored band, which shades off gradually from red to violet, is called a **spectrum.** This shows that ordinary white light is complex and contains different kinds of light. The light which is refracted least, the eye recognizes as red, and that which is refracted most, as violet. It will be shown later that the physical property of light which determines this difference in refrangibility is the **wave length.**

To show that the prism itself did not produce the different colors, but simply separated various kinds of light already present in the beam

of light, Sir Isaac Newton placed a second prism in the spectrum, so that only violet light fell on it. He found that the violet light was again refracted, but that there was no further change in color. He also found that when these dispersed colored lights were brought together by a converging lens, white light was the result.

483. Achromatic lenses. When sunlight passes through an ordinary double convex lens made of a single piece of glass, the light is refracted and converges at a point called the focus. But the light is also dispersed, just as in a prism, and the focus for red light (*R* in figure 552) is at a greater distance from the lens than that for violet light *V*. Such a single lens cannot give a sharp image of an object illuminated by ordinary white light, for all the lines of separation between light and dark portions of the image will be colored.

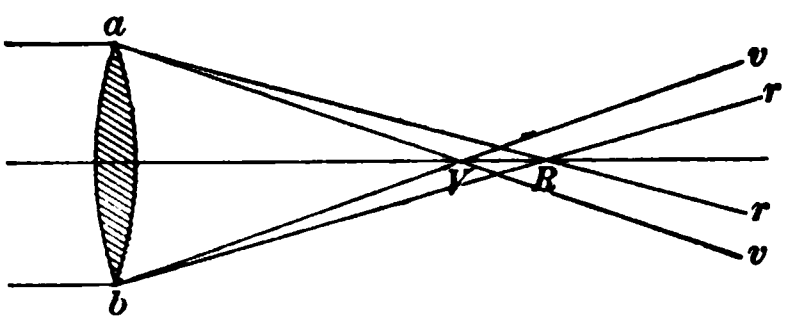


Fig. 552. Dispersion produced by a lens.

This defect, which is known as **chromatic aberration**, may be remedied by combining a lens of crown glass with a lens of flint glass, as shown in figure 553. By carefully designing the two component lenses, it is possible to make **achromatic lenses**, which produce the necessary refraction without dispersion.

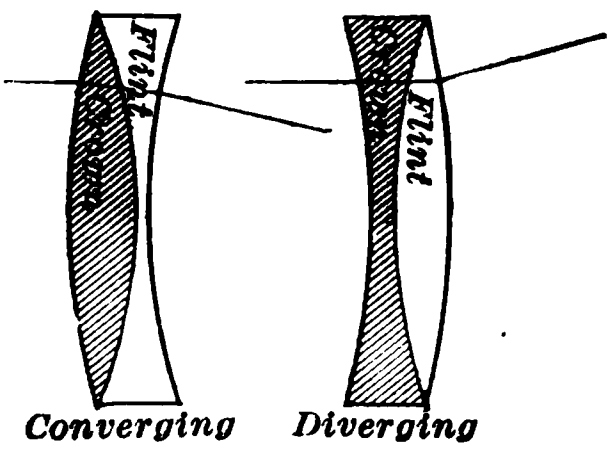


Fig. 553. Achromatic lenses.

484. Spectroscope. In the spectrum produced by a prism the different colors overlap each other to some extent. This can be remedied by using a **spectroscope**. There are four main parts in a spectroscope (Fig. 554): the **collimator**, which has a slit at one end and a convex lens at the other; a **prism** commonly of flint glass; a **telescope**, which has an object glass and eyepiece; and a **scale tube**, which has a ruled scale at one end and a lens at the other. The slit in the

collimator is at the principal focus of the lens; and so light diverging from the slit is made parallel by the lens before it reaches the prism. Here it is refracted and dispersed, each color going off as a parallel beam in its own direction. The

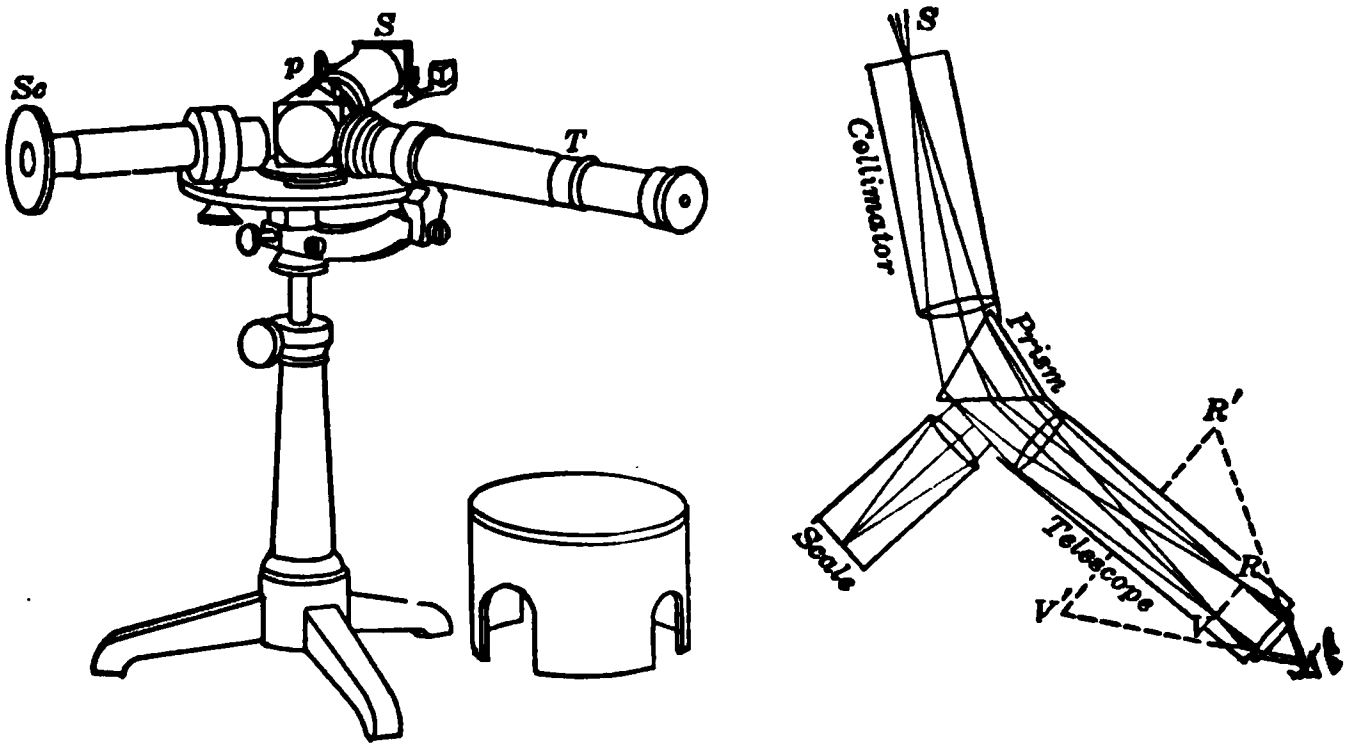


Fig. 554. Bunsen spectroscope with diagram.

telescope forms a sharply defined image of the spectrum. The scale tube, which is added to locate the parts of the spectrum, is so mounted that the light from the illuminated scale is reflected from the second face of the prism into the telescope along with the spectrum.

485. Kinds of spectra. The spectrum of sunlight, or **solar spectrum**, is frequently seen after a shower in summer time in the form of a rainbow. The sunlight is refracted and dispersed by the raindrops. When the solar spectrum is studied minutely with a spectroscope, it is found not to be a continuous band of colors, but to be crossed by many vertical dark lines. Since these lines were first carefully studied by a German astronomer, Fraunhofer, they are known as **Fraunhofer lines.**

Not all sources of white light give these dark lines. For example, an electric arc lamp, an incandescent lamp with a tungsten filament, an ordinary gas flame, which contains many

Solar

Na

Li

K

Ca

Ba

Hg

particles of incandescent solid carbon (soot), and indeed all **incandescent solids give continuous spectra.**

The spectrum of an incandescent vapor or gas is quite different. It is a **bright-line spectrum**, and is characteristic of the substance used. (See SPECTRUM CHART on the opposite page.)

If we dip a platinum wire or bit of asbestos into a solution of common salt (sodium chloride) and hold it in a blue Bunsen flame, we get a bright yellow flame. If we examine this flame with a spectroscope, we see a bright yellow line, where the yellow part of the spectrum would be. This yellow light comes from incandescent sodium vapor.

If we repeat the experiment with a wire dipped in a chemical called lithium chloride, we get a red flame, which gives in the spectroscope two bands, one yellow and one red. Calcium chloride also gives two bands, green and red. (The yellow band, which is likely to be seen also, is due to sodium present as an impurity.)

486. Spectrum analysis. When the spectroscope is used to examine the spectrum of various gaseous substances, it is found that each element has its own characteristic bright-line spectrum. It may be simple, as in the case of sodium; or it may be complex, as in the case of iron vapor, which has more than four hundred lines. Since a very small quantity of a substance will show its characteristic spectrum lines (less than one millionth of a milligram of sodium can be detected), we have a very delicate method of analyzing substances. **Spectrum analysis** was first used by the chemist Bunsen in 1859.

487. Absorption spectra. Kirchhoff (1824–1887), while a professor of physics at Heidelberg, worked conjointly with Bunsen in these investigations with the spectroscope. Kirchhoff observed that when he held an alcohol flame colored with common salt in front of the slit of the spectroscope and allowed a beam of sunlight to pass through the slit, the sodium line became especially dark and sharp, although he had expected it to be especially bright. Evidently the sunlight had been in part absorbed by the yellow sodium flame and the special part which the sodium flame itself ordinarily gives out had been removed. Kirchhoff concluded that, in general:

A glowing gas absorbs from the rays of a hot light-source those rays which it itself sends forth.

A demonstration of Kirchhoff's law may be conveniently performed with the apparatus shown in figure 555. The source of light

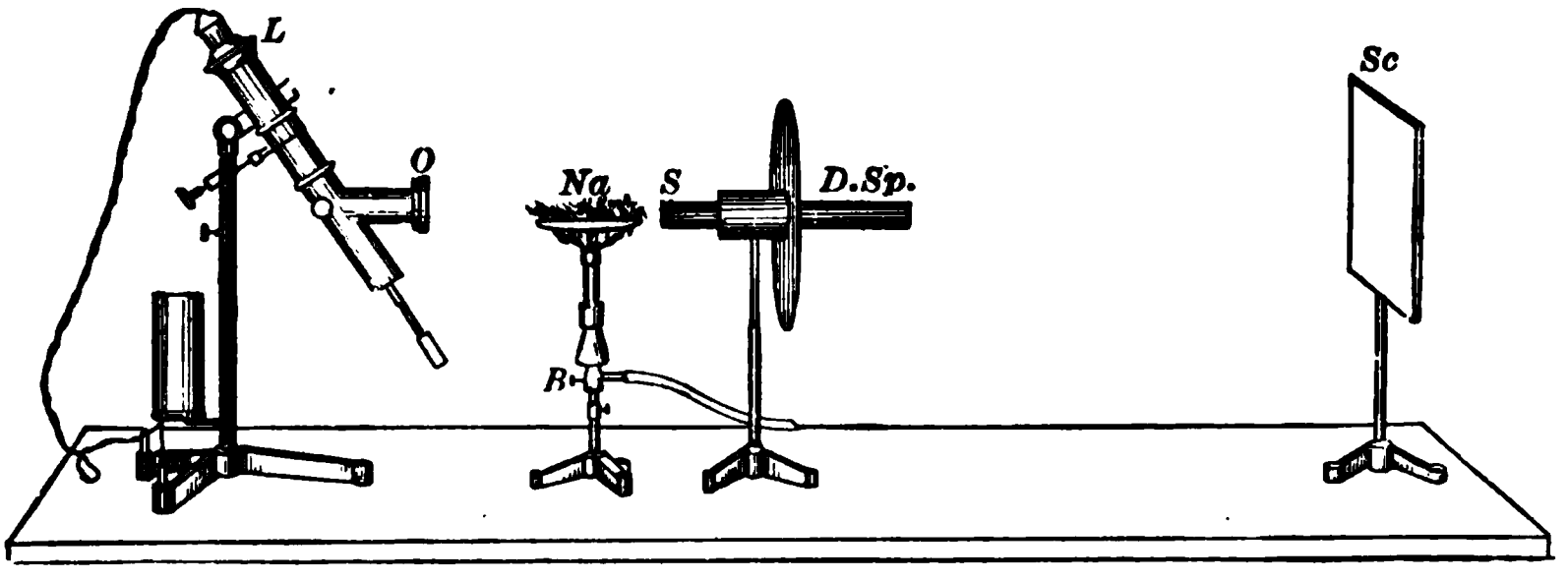


Fig. 555. Absorption of yellow light by sodium vapor.

L is the glowing positive carbon of the electric arc, whose rays are made parallel by a lens *O*. Two strips of asbestos board, soaked in salt water, are heated by a wing-top Bunsen burner. The light from the electric arc passes directly through the sodium flame into a " direct-vision " spectroscope, which disperses the light on the screen *Sc*.

First we set the sodium-flame burner to one side, and produce a continuous spectrum on the screen. Then we bring the sodium flame into position, and we see in the yellow portion of the spectrum a dark line.

If we cover the lens *O* with an opaque cardboard, the spectrum disappears, but in the place of the dark line we now have the bright sodium line. Or, if we place a small white screen with a narrow slit where the dark line is located just in front of the screen *Sc*, the dark line on the screen *Sc* appears as a yellow line. This shows that the dark absorption band is not absolutely black, but is so much less intense than the direct radiation from the arc that it appears black by contrast.

It is evident, then, that *to produce dark absorption lines the absorbing vapor must be colder than the luminous source.*

488. Meaning of Fraunhofer lines. We have said in section 485 that the solar spectrum contains a large number of dark lines. Kirchhoff concluded that these dark lines were caused by the presence in the glowing solar atmosphere of those substances which themselves produce bright lines in

the same positions. The core of the sun is at a very high temperature and gives forth a continuous spectrum. But this core is surrounded by a layer of gas which is cooler and absorbs those light rays which it itself would send out. On this basis he concluded that such metals as iron, magnesium, copper, zinc, and nickel exist as vapors in the solar atmosphere. After much study he found that the bright-line spectra of all the elements on the earth correspond in position to certain Fraunhofer lines, and concluded that all the elements found on the earth exist in the atmosphere of the sun. There were certain other Fraunhofer lines whose elements were not known on the earth in Kirchhoff's time. One of these new elements, helium, has since been found on the earth, and perhaps the others also will sometime be found.

Kirchhoff's explanation of the Fraunhofer lines was epoch-making. Helmholtz said, " It has excited the admiration and stimulated the fancy of men as hardly any other discovery has done, because it has permitted an insight into worlds that seemed forever veiled to us."

489. The nature of light. We have said that light is considered to be a vibration of the ether. That is, light and heat are both forms of radiant energy. But we must not think that this has always been the accepted theory. To be sure, in the seventeenth century the great Dutch physicist, Huygens, worked out the wave theory very completely; but his rival, Sir Isaac Newton, in England, maintained the older corpuscular theory, according to which light consists of streams of very minute particles, or corpuscles, projected with enormous velocity from all luminous bodies. Newton's reputation as a scientist was so great that his unfortunate corpuscular theory controlled scientific thought for more than a hundred years; and it was not until the beginning of the nineteenth century that the experiments of Thomas Young in England and of Fresnel in France established the wave theory on a firm basis.

490. Different colors due to different wave lengths. It is

now possible to measure directly the length of the waves of light of different colors, and to show that the waves of red light are longest and those of violet are shortest. So in the dispersion of sunlight by a *prism*, it is the *long* waves (red) which are refracted *least*, and the *short* waves (violet) which are refracted *most*. The following table gives the approximate wave lengths of some of the colors.

WAVE LENGTHS OF LIGHT

Red . . .	0.000068 cm.	Green . . .	0.000052 cm.
Orange . . .	0.000065 cm.	Blue . . .	0.000046 cm.
Yellow . . .	0.000058 cm.	Violet . . .	0.000040 cm.

491. Colors of objects. The color of any object depends (1) on the light which illuminates it, and (2) on the light it reflects or transmits to the eye.

A skein of red yarn held in the red end of the spectrum appears red. But when held in the blue end of the spectrum, it appears nearly black. Similarly a skein of blue yarn appears nearly black in all parts of the spectrum except the blue, where it has its proper color.

Another striking experiment is to illuminate an assortment of brilliantly colored worsteds or paper flowers by the light from a sodium flame. This light contains only one group of wave lengths. Those worsteds which reflect these particular wave lengths look yellow, while those which do not reflect them look dark.

Thus it appears that when a piece of paper looks white in daylight, it is because it reflects all wave lengths equally, and when a piece of cloth looks red in daylight, it is because it reflects only those long waves which produce red light. If the white paper receives only waves of red light, it appears red, and if the red cloth receives only waves which have no red in them, it appears dark. That is, *the color of an* ***opaque*** *object depends on the wave length of the light it reflects.* The Cooper-Hewitt mercury-vapor lamp is a very efficient electric lamp; but it cannot be used in places where colors must be distinguished, for it does not furnish waves of red light.

If we place a piece of red glass in the path of the light which is dispersed by a prism to form a spectrum, we see only the red portion of the spectrum. This shows that all the wave lengths except the red have been absorbed. In a similar way a green glass lets the green light through, but greatly reduces the other parts of the spectrum. If we insert both the green and the red glasses, the spectrum almost vanishes.

Thus we see that *the color of a transparent object depends on the wave length of the light it transmits.* Ordinary red glass, such as photographers use for their red lanterns, transmits freely only red light, and absorbs almost completely the yellow, green, blue, and violet light, which especially affect the chemical compounds used on photographic plates.

492. Mixing colors and mixing pigments. There are other colors besides white which do not have a definite wave length. A mixture of several wave lengths may produce the same sensation as a single wave length.

Let us rotate a disk part red and part green (Fig. 556) so rapidly that the effect on the eye is the same as though the colors came to the eye simultaneously. The revolving disk appears yellow, much like the yellow of the spectrum. By mixing red and blue we get purple, which is not found in the spectrum. By mixing black with red or orange or yellow we get the various shades of brown.

The colors of the spectrum are called **pure** colors and the others **compound** colors. If yellow light is mixed with just the right tint of blue, white light is produced. Such colors are called **complementary** colors.

Fig. 556. Newton's color disk.

Let us pulverize a piece of yellow crayon and a piece of blue crayon. If we mix the two together about half and half, the color of the resulting mixture is bright green.

This shows that while mixing yellow and blue **light** produces white, mixing yellow and blue **pigments** produces green. This is because the yellow pigment absorbs or subtracts from

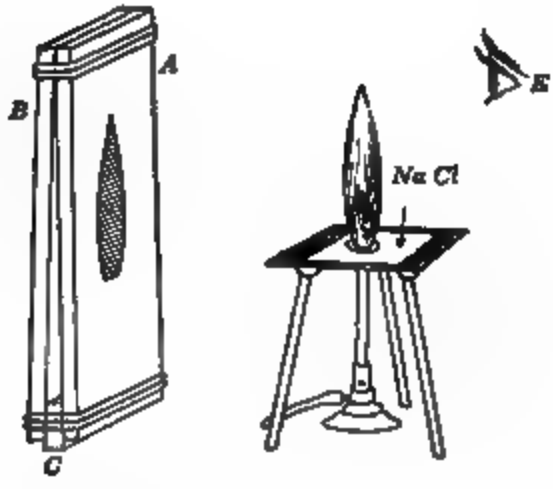


Fig. 557. Interference of sodium light waves.

white light all *except yellow and green*, and the blue pigment subtracts all *except blue and green;* therefore the only color not absorbed by one pigment or the other is *green*. In other words, *in mixing pigments, the color of the mixture is that which escapes absorption by the different ingredients.*

493. Colors of thin films. The brilliant colors produced by the reflection of light from thin transparent films, like the film of a soap bubble, furnish one of the strongest arguments for the wave theory of light.

Let us bind two pieces of plate glass *A* and *B* (Fig. 557) together with rubber bands, in such a way that they will be separated at one end by a piece of tissue paper *C*. If we hold the glass strips behind a sodium flame, we see in the reflected image of the yellow flame a series of fine horizontal dark lines.

To explain this effect we draw a much-enlarged section of the glass plates with the wedge of air between. In figure 558 let *AB* and *BC* be the glass plates, and let the yellow sodium light be coming from the right as a series of transverse waves, which we can represent by the wavy lines. We know that this light is in part transmitted and in part reflected at each glass surface. But we are interested only in what happens at the interior faces *AB* and *BC* of the plates. Let the full line *DE*

Fig. 558. Explanation of formation of bright and dark lines.

represent the light reflected at the point D on the surface AB, and let the dotted line $D'E$ represent the wave reflected at D' on the surface BC. If the distance from D to D' is such as to make one reflected wave just half a vibration behind the other in phase, they will **interfere** and neutralize each other. At this point we have a dark line. But at another point F the distance between the plates may be such that the wave reflected at F' coincides with and **reënforces** the wave reflected at F. At this point we see a bright yellow line. If we select any two *consecutive* dark lines, we know that the *double* path between the plates at one line must be just one wave length longer than that at the other line. This gives us a method of computing the length of a wave.

For example, suppose the length of the air wedge is 100 millimeters, the thickness of the paper is 0.03 millimeters, and the distance between adjacent dark lines with sodium light is 1 millimeter. Since the width of the wedge increases 0.03 millimeters in a distance of 100 millimeters, it increases 0.0003 millimeters in 1 millimeter, and the increase in the double path between adjacent dark lines would be 0.0006 millimeters. This is approximately the wave length of sodium light.

494. Sunlight decomposed by interference. Let us dip a clean wire ring into a soap solution and set it up so that the film is vertical. The water in the film will run down to the lower edge, and the film becomes wedge-shaped. Let a beam of sunlight, or the light from a projection lantern, fall on this soap film and be reflected on a white screen Furthermore, let a convex lens be arranged, as in figure 559, so as to produce a sharp image of the film F on the screen. We see on

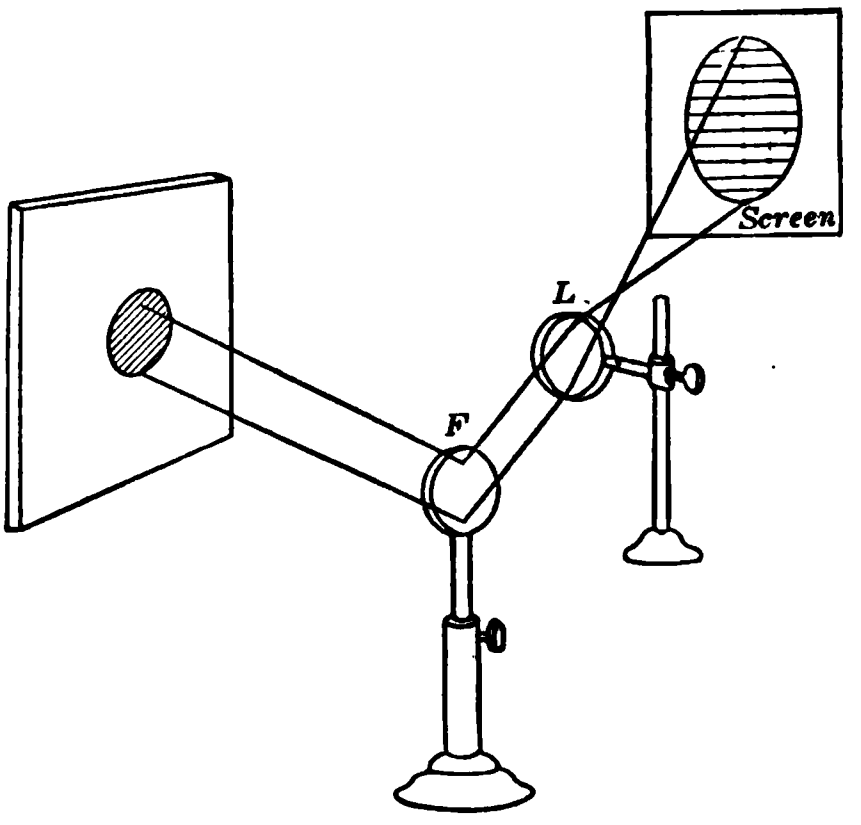


Fig. 559. Interference of white light in soap film.

the screen a series of horizontal bands of the various colors of the spectrum.

The white sunlight is composed of different colors and so of different wave lengths. The interference of the red waves takes place at one point, and that of the yellow at a different point. Where there is interference of the red waves, the complementary color, a sort of bluish-green, is left; and where there is interference of the yellow waves, the color complementary to yellow, namely, blue, is produced. Thus we have a series of colored bands which are complementary to all the colors of the spectrum.

Many beautiful color effects are caused by the interference of light waves in very thin films. The colors of oil films on the surface of water, of the thin films of oxide on metals and on Venetian glass, of the feathers of the peacock, and of changeable silk are due to the interference of light waves.

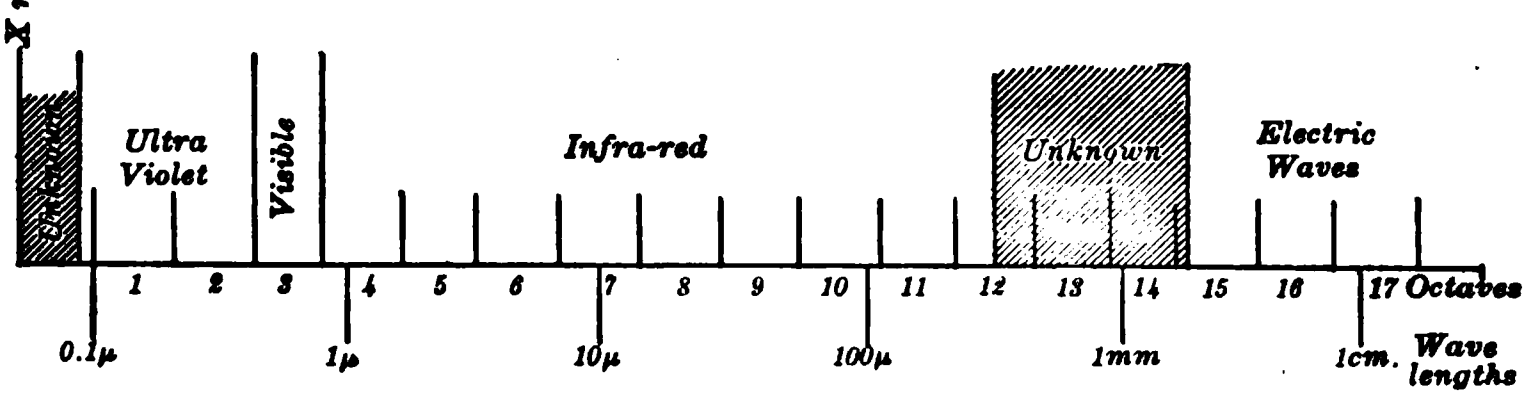


Fig. 560. Distribution of waves of varying lengths.

495. Infra-red and ultra-violet rays. By means of sensitive heat-absorbing instruments we have come to know that the sun is sending out not only the light waves which affect the optic nerve, but also other **longer** ether waves which, though invisible, yet can produce strong heating effects. They are called **infra-red rays** (Fig. 560). We have also learned, by photographing the spectrum of the sun, that it is sending out rays too **short** to be seen, which affect a photographic plate, and are called **ultra-violet rays.**

496. Electromagnetic theory of light. As we have seen, Faraday was led to believe that his "lines of force" transmitted

electricity and magnetism through some medium, called the ether. A few years later Maxwell developed this theory of Faraday's and put it on a mathematical basis. The theory was finally confirmed in 1888 by a young German, Hertz. His experiments proved that electric waves really exist, and have the same velocity as light, although they are sometimes many meters long. These electromagnetic waves are reflected and refracted like light waves. Therefore, we feel sure that **light waves are electric waves.** This conception, and that of the conservation of energy, are the most remarkable achievements of physics in the nineteenth century.

SUMMARY OF PRINCIPLES IN CHAPTER XXII

White light **is a mixture of a vast number of waves of different lengths.**

Difference in color **corresponds to difference in wave length, the red waves being longer than the violet.**

Wave length of visible spectrum ranges from about 0.000068 centimeters (red) to about 0.000040 centimeters (violet).

Short **waves are *most* refracted by prisms and lenses.**

Continuous **spectrum formed by incandescent *solids*.**

Bright-line **spectrum formed by incandescent *gases*.**

Dark-line **spectrum formed by incandescent solid shining through an absorbing layer of *cooler* gas.**

Color of an object depends on wave lengths reaching eye.

Colors of thin films due to disappearance of certain wave lengths by *interference*.

QUESTIONS

1. A clean platinum wire is held in a blue Bunsen flame and observed through a spectroscope. What sort of spectrum is formed?
2. What kind of Fraunhofer lines does one get in moonlight?
3. Why are "color filters" used in photography?
4. What causes the various colored lights in fireworks?

5. Why does a blue dress look black by the light of a kerosene lamp?

6. Why does a reddish lampshade make a room seem more cheerful at night?

7. How are colored motion pictures produced?

8. Why are glass lenses not used in the ultra-violet microscope?

9. The only light used in a photographic dark room passes through a red window. Explain.

10. Explain why the complementary of any one of the spectrum colors is a complex tint and not a pure color.

11. Explain why the colored bands produced by the interference of white light by a soap film are complex tints and not pure spectrum colors.

PRACTICAL EXERCISES

1. Printing in colors. Examine under a magnifying glass a colored picture post card. Find out how ordinary black and white half-tones are made and how the three-color half-tones are produced. Get sample prints from some large printing establishment to illustrate the various stages in the process.

2. Color blindness. Test yourself and your friends for color blindness by the use of Holmgren's Test Wools. Find out what the modern theory is as to the cause of this defect. In what occupations would this defect prove a serious handicap?

3. The colors of the rainbow. Consult larger books in physics, such as *Kimball's* College Physics, for the explanation of the colors of the rainbow. Make a miniature rainbow on a screen by holding a glass bulb (about 1½ or 2 inches in diameter) filled with water in the path of a beam of sunlight (or of an arc light) in a darkened room (Fig. 561). Explain the colors.

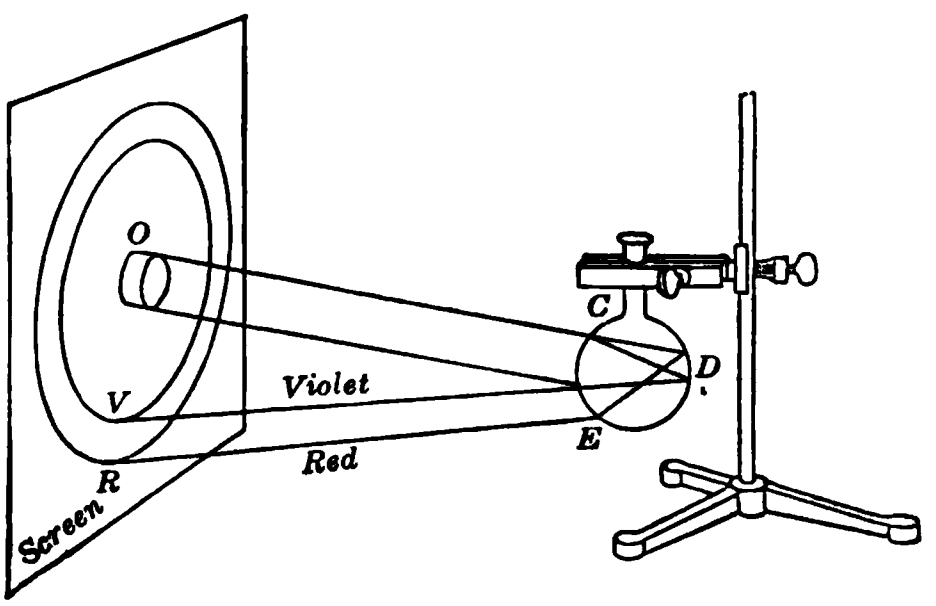


Fig. 561. Making a miniature rainbow.

CHAPTER XXIII

ELECTRIC WAVES: ROENTGEN RAYS AND RADIOACTIVITY

Discharge of condenser is oscillatory — electric resonance — electric waves — detectors — radio telegraphy and telephony. Discharge through gases — cathode rays — Roentgen rays. Radioactivity — radium — its radiations — disintegration — uses — energy changes.

Electric Waves

497. Discharge of Leyden jar is oscillatory. In 1842 Joseph Henry discovered that when a Leyden jar was discharged through a coil of wire surrounding a steel needle, the needle was magnetized. Not only that, but he was astonished to find that sometimes one end was made the north pole and sometimes the other, even though the jar was always charged the same way. He accounted for this fact by supposing that the discharge current kept reversing back and forth, that these oscillations gradually died away, and that the direction in which the needle was magnetized depended on which way the last perceptible oscillation happened to go. This oscillatory current is represented by the curve in figure 562.

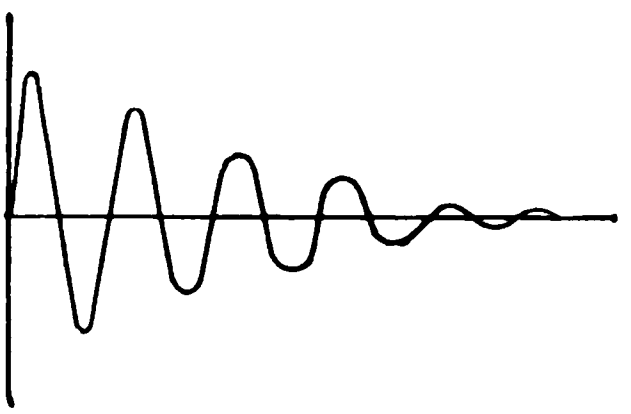


Fig. 562. Curve of oscillatory electric discharge.

A few years later Lord Kelvin, the great English physicist and electrical engineer, proved mathematically that the discharge must be oscillatory. Finally, in 1859, Feddersen succeeded in photographing an electric spark by means of a rapidly rotating mirror. Figure 563 shows such a photograph. The oscillatory discharge is drawn out into a band by the rotating

mirror, and thus makes a zigzag trace on the camera plate. From this experiment it is possible to calculate the time of one oscillation. It is exceedingly short, varying from one one-thousandth to one ten-millionth of a second.

Fig 563. Photograph of oscillations of electric spark.

498. Electrical resonance. We have already seen, in studying sound waves, that two objects having the same vibration frequency tend to vibrate in sympathy, and that this property of vibrating bodies is called resonance.

Let us stretch a piece of rubber tubing between two supports and suspend two weights x and y by threads of equal length, as shown in figure 564. If we set one pendulum y swinging, the other pendulum x soon begins to swing, and the first one dies down as energy flows across to the other. This will happen only if the pendulums are of the same length and so of the same frequency. That is, *resonance* is necessary for the transfer of energy.

Now, the frequency of the oscillatory current produced by discharging a condenser depends upon the capacity of the condenser, and on the resistance and inductance of the circuit through which the current surges. Therefore, if two Leyden-jar circuits have the same capacity, the same self-induction, and the same resistance they will have the same frequency, and one circuit will influence the other.

Let two Leyden jars A and B (Fig. 565) be of the same size and thickness of wall. To the jar A is connected a rectangular circuit of thick wire, one end of which touches the outer coating of the jar, while the other is separated from the knob of the jar by a small spark gap. The jar B is connected to a similar circuit, except that the end CD of the rectangle can be slid back and forth, and there is no spark gap. Finally, let the inner

Fig 564. Resonance in two pendulums.

coating of B be connected to its outer coating by a strip of foil cut sharply across at X.

If we place the two electrical circuits a foot apart and parallel, and send sparks across the gap of A by means of an induction coil, we find that there is a position of the slider CD such that tiny sparks appear at the gap X in the foil strip on B. When the slider is moved a short distance from this position either way, the sparks at X cease.

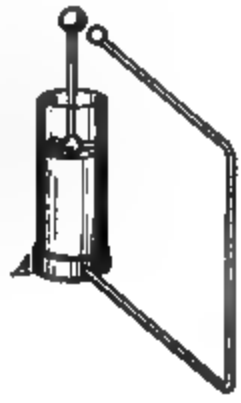


Fig 565. Resonance between two electrical circuits.

This phenomenon is called **electric resonance.** Although there is no connection between the two circuits, yet the energy in one circuit surges over into the other, which is in tune with it, and causes a spark there. In explanation of this experiment, and many others, we assume that an oscillatory discharge or spark sends out **waves** in the surrounding ether. The ether does for the electric circuits what the rubber tubing did for the pendulums. It serves as a medium for the transfer of energy.

These electric waves were first detected and measured by Heinrich Hertz (Fig. 566), in 1888, and are therefore called **Hertzian waves.** They travel with the same velocity as light.

Fig. 566. Heinrich Rudolf Hertz (1857–1894) Discovered the electromagnetic waves predicted by Maxwell.

499. Electric-wave detectors. The **microphone**, described in section 362, is an excellent wave detector. Another form, called a **crystal detector** (Fig. 567), consists of a piece of silicon, or of any one of several crystalline substances, such as galena, embedded in soft metal on one side and touched on the other by a metal point. The operation of the crystal detector seems to depend on some mysterious property whereby it lets electricity flow through it in one direction much more easily than in the other; in short, it acts as a rectifier.

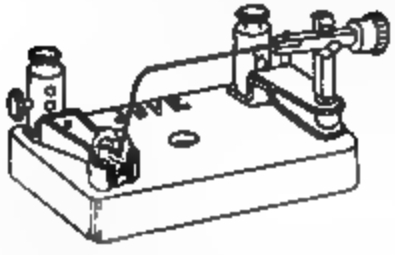


Fig. 567 Crystal detector.

A more recent and far more sensitive detector is the **vacuum-tube detector**. This works on essentially the same principle as the vacuum-tube rectifier, which has already been described in section 384. In practice it is now usually provided with *three electrodes*, — a tungsten filament, a plate, and in addition a third electrode, called a **grid**, in between the first two electrodes. Figure 568 shows the external appearance of one type of vacuum tube, and figure 568A is a diagram to explain its action. The filament when glowing emits electrons. The effect of the third electrode, or grid, is like that of a shutter which, opening or closing, controls the flow of electrons through it from the filament to the plate. When the grid is charged by a feeble source of alternating current positively or negatively with respect to the filament, the flow of electrons is accelerated or retarded. Thus a considerable

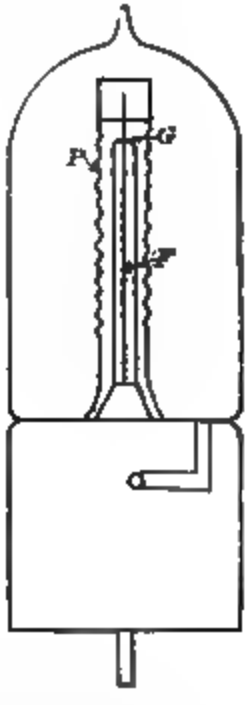


Fig. 568. Three-electrode vacuum tube: *P*, plate; *G*, grid; *F*, filament.

current flowing from the plate to the filament may be controlled by an extremely small amount of energy used to charge the grid. This is the principle of the vacuum-tube detectors and of the telephone amplifiers used in long-distance telephony and radio telephony.

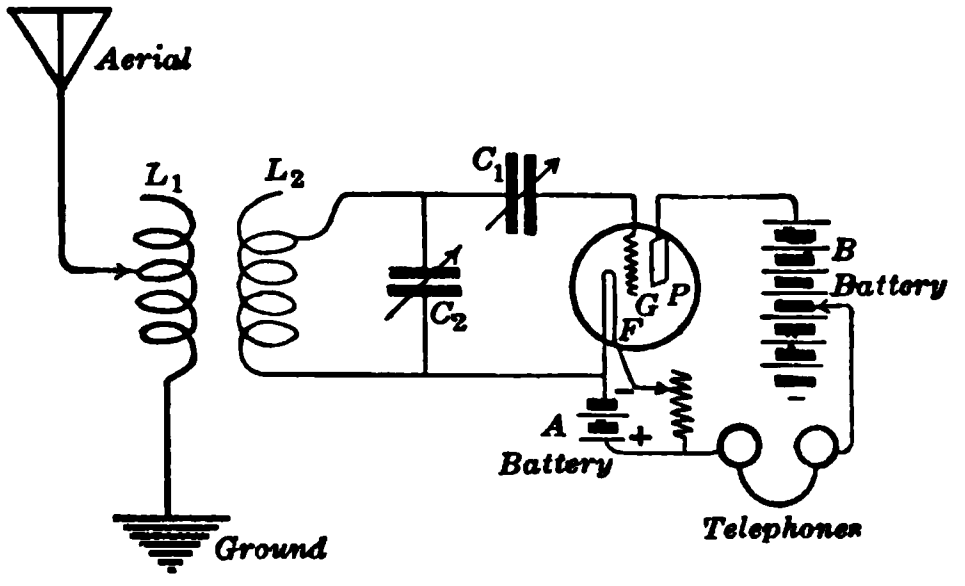


Fig. 568A. Diagram showing the use of a vacuum-tube detector in a receiving circuit for radio telegraphy and telephony.

500. Radio telegraphy. Through the efforts of the Italian inventor, Marconi, and many others, electric waves are now being extensively used commercially in radio telegraphy.

A simple **sending station**, such as Marconi used in his earliest experiments, is shown in figure 569. The essential part is a conductor, called the **aërial** or **antenna**, extending to a considerable height above the ground. Powerful electrical oscillations are set up in this conductor like the oscillations in the spark discharge shown in figure 562. These send waves out through the ether, just as a stick laid on water and shaken up and down sends out ripples over the surface of the water.

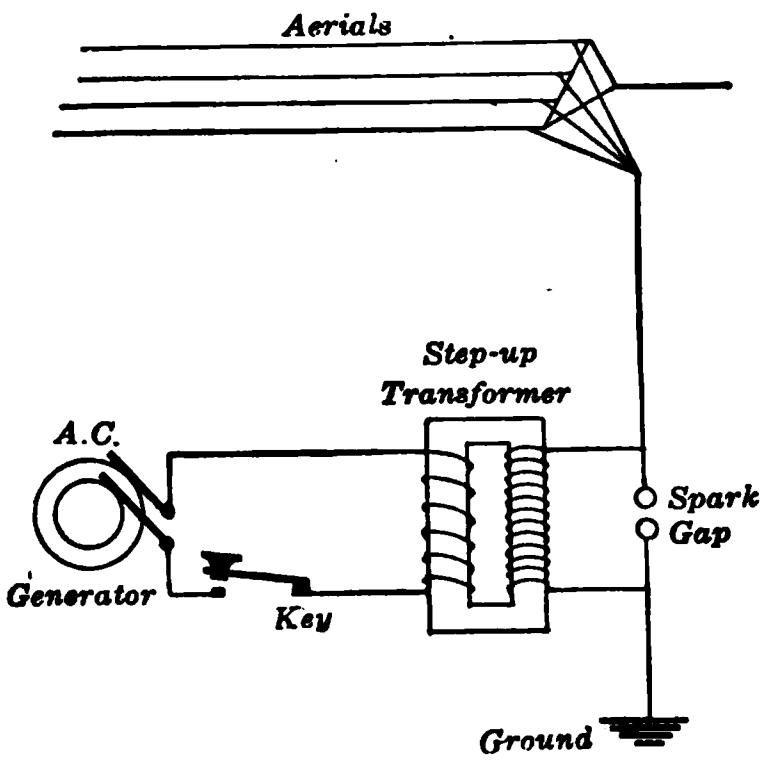


Fig. 569. Simple sending station.

One way to set up oscillations in an aërial is to put a spark gap in it, and to send sparks across this gap by means of an induction coil fed by batteries, or by means

of an alternator and step-up transformer, as shown in figure 569.

The simplest kind of **receiving station** is represented in figure 570. There is an aërial like that at the sending station except that, instead of a spark gap, it contains a detector of some sort. In parallel with this detector is a telephone receiver. Every time a train of waves reaches such a receiving station, some of the energy is absorbed by the aërial, and electrical oscillations are set up in it. These cannot get through the telephone because of its inductance, and so they have to pass through the detector. But since a crystal detector lets more electricity through one way than the other, an excess of electricity accumulates in the antenna. This excess then discharges through the telephone, and the diaphragm moves over and back once.

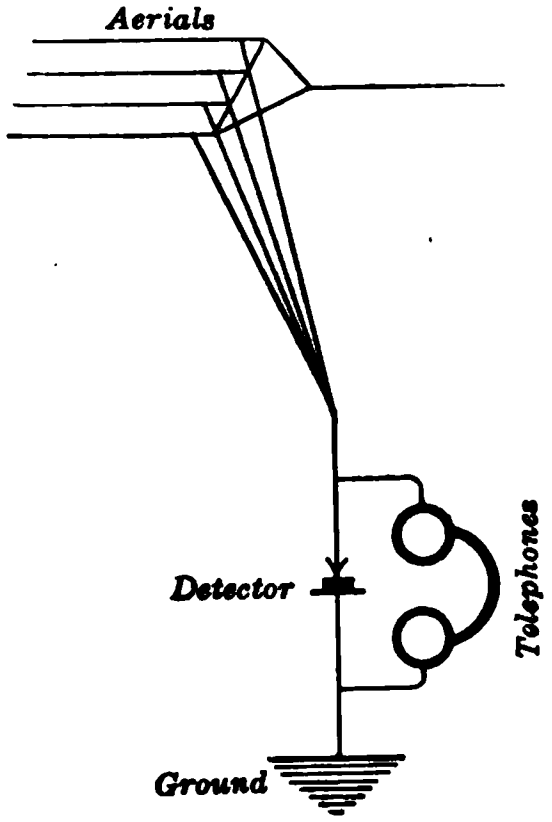


Fig. 570. Simple receiving station.

Since this happens every time a train of waves comes in, which is many times every second, the telephone diaphragm is kept vibrating and emits a steady musical note as long as the key of the sending station is closed. The duration of this note can be made shorter or longer by holding the sending key down a shorter or a longer time; and so the dots and dashes of the International Morse code can be transmitted.

The circuits used in commercial wireless telegraphy are, of course, much more complicated than these, because it is necessary to " tune " the sending and receiving stations accurately to the same frequency, and to make them insensitive to waves of any other frequency, so that one pair of stations may not interfere with another. For an explanation of commercial sending and receiving stations, the reader may consult any of the numerous popular or technical books on radio telegraphy.

501. Radio telephony. Not long after the first successful experiments in radio telegraphy, attempts were made to transmit speech by means of electromagnetic waves. Experiments seem to show that *undamped continuous oscillations of very high frequency are necessary for radio-telephone work.* The frequency of this alternating current must be above the limit of audibility and is often about 100,000 cycles per second. If such a persistent series of oscillations passes through a microphone transmitter at the sending station, and if the resistance of this microphone is made to vary by the voice, then the sequence of the waves is modified in intensity, and the amplitude of the high-frequency waves varies in a way which corresponds to the voice. These variations persist in the rectified current through the telephone at the receiving station and are heard as spoken words.

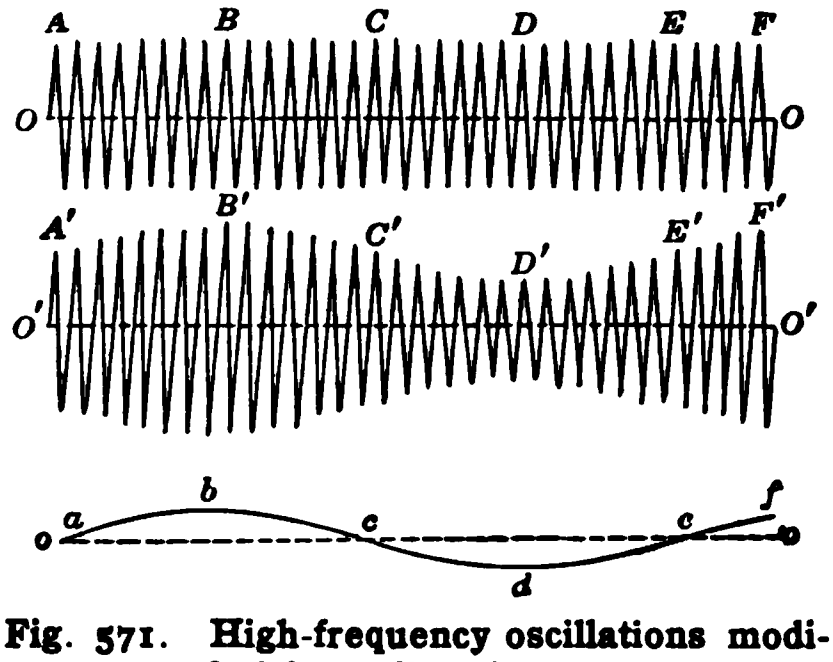


Fig. 571. High-frequency oscillations modified for radio telephony.

Perhaps this will be made clearer by studying the diagrams in figure 571. The rapid oscillations $OABCDEF$ represent the high-frequency alternating current steadily supplied to the sending antenna when no telephonic transmission occurs. But when a microphone transmitter is put into the sending circuit, the amplitude of these outgoing waves is altered according to the diagram $O'A'B'C'D'E'F'$, and the diaphragm of the telephone connected to the receiving antenna vibrates so as to give out the wave *a b c d e*.

For both radio telegraphy and radio telephony the receiving circuits are identical. The main problem of radio telephony has been the production of continuous-wave high-frequency oscillations and the modulation of these oscillations through the

human voice. At the new radio central station on Long Island, which has a transmission range that is practically world-wide, high-frequency alternators are installed. For low-power commercial sets suitable for marine, land, or airplane service, three-electrode vacuum tubes are used both for generating the high-frequency oscillations and for modulating them. For further details about the theory and practical use of vacuum tubes in radio telephony, the reader should consult some of the special books * on radio communication.

Electrical Discharge through Gases

502. Sparking voltage. The voltage needed to make a spark jump between two knobs depends on several factors, such as the size of the knobs, the distance between them, and the atmospheric pressure. It takes less voltage to cause a spark to jump between two sharp points than between two round balls. Thus, the **sparking voltage** for two sharp points 1 centimeter apart is about 7500 volts, while that for two round balls 1 centimeter in diameter and 1 centimeter apart is about 27,000 volts. The sparking voltage between two sharp points varies so nearly as the distance that this is a method used to measure very high voltages.

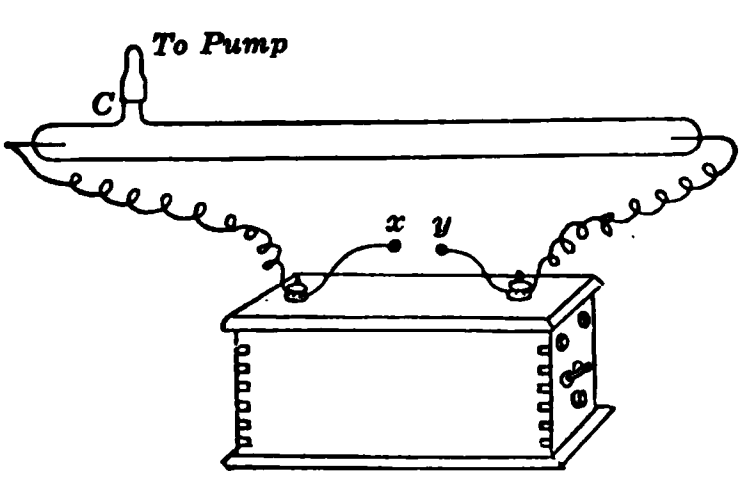


Fig. 572. Discharge in a partial vacuum.

To show the effect of atmospheric pressure, we may connect a glass tube 2 or 3 feet long with an induction coil, as shown in figure 572. The tube is connected with a vacuum pump by a side tube. When the coil is first started, the discharge takes place between x and y, the terminals of the coil, which are only a few millimeters apart; but when the air is

* The Principles Underlying Radio Communication. — Radio Pamphlet No. 40; United States Government Printing Office, Washington, D. C.

pumped out of the tube, the discharge goes through the long tube instead of across the short gap xy. This shows that the sparking voltage decreases when the pressure is diminished.

503. Discharges in partial vacua. Reducing the atmospheric pressure between two points makes it easier for an electric discharge to pass, until a certain point in the exhaustion is reached. Then it begins to be more difficult. At the very highest degree of exhaustion yet attainable, it is hardly possible to make a spark pass through a vacuum tube.

The changes in the appearance of such a tube as the exhaustion proceeds are very interesting. At first the discharge is along narrow flickering lines, but as the pressure is lowered, the lines of the discharge widen out and fill the whole tube until it glows with a steady light. With still higher exhaustion, a soft, velvety glow covers the surface of the negative electrode, or cathode, while most of the tube is filled with the so-called positive column, which is luminous and stratified, and reaches to the anode. The so-called Geissler tubes (Fig. 573) are little tubes of this sort which are usually made in fantastic shapes and serve as pretty toys. The color of the light from a Geissler tube depends on the gas which is in the tube, and on the kind of glass used.

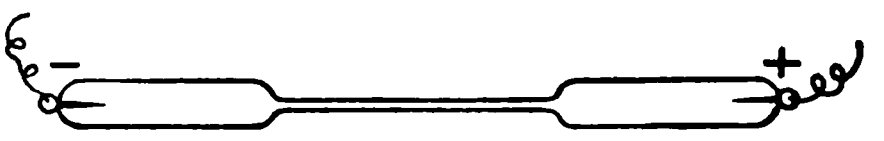


Fig. 573. Geissler tube, made to study spectra of hydrogen.

504. Cathode rays. When the exhaustion of a tube is carried to a very high degree, so that the pressure is equal to about 0.0001 of a millimeter of mercury, the positive glow is very faint and the dark space around the cathode is pervaded by a discharge. An invisible radiation streams out nearly at right angles to the cathode surface, no matter where the anode is located in the tube. This radiation from the cathode is called **cathode rays** and shows itself in several ways: *first*, by a yellowish green fluorescence wherever it strikes the glass of

the tube; *second*, by the fact that it can be brought to a focus, where it produces intense heat; and *third*, by the sharply defined shadow which a metal interposed in its path produces in the fluorescence on the end of the tube.

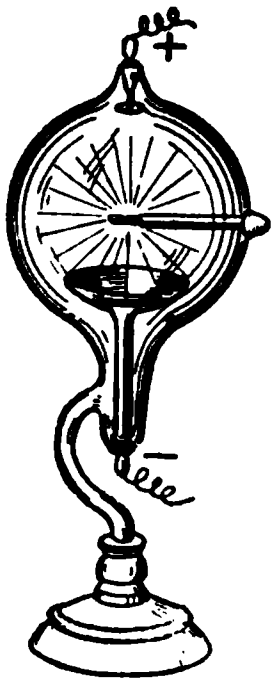


Fig. 574. Heating effect of cathode rays.

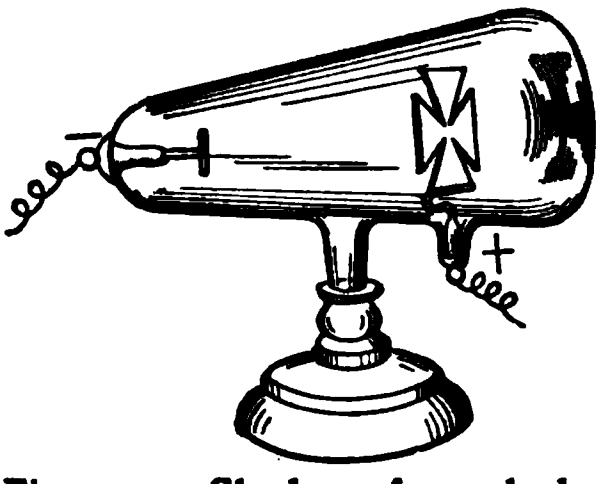


Fig. 575. Shadow formed by cathode rays.

A vacuum tube, arranged as in figure 574, shows the heating effect of the cathode rays. When an induction coil sends a discharge through the tube from top to bottom, the cathode rays are focused on a piece of platinum, which becomes red hot.

Another vacuum tube, arranged as in figure 575, shows that a shadow is formed on the end of the tube by an aluminum cross.

505. What are cathode rays? A vacuum tube, made as in figure 576, sends a narrow band of cathode rays through the slit *s* in the aluminum screen *mr* against a fluorescent screen *f* slightly inclined to them. When a strong magnet *M* is held near the side of this tube, it is found that the stream of cathode rays is deflected in the direction which would be expected if they were a stream of negatively charged particles. From this and other experiments we believe that *cathode rays are streams of* ***electrons*** *shot off from the surface of the cathode at very high velocity.*

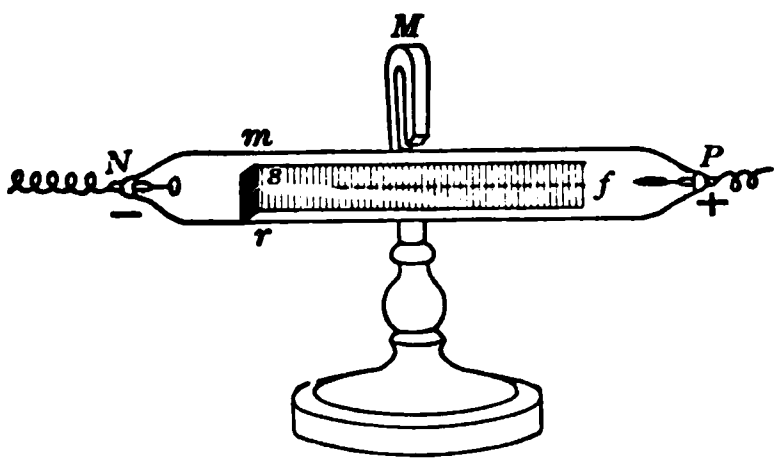


Fig. 576. Bending of cathode rays by a magnet.

J. J. Thomson, the English physicist, has estimated from various experiments on cathode rays that these electrons have each a mass about sixteen hundred times smaller than that of a

hydrogen atom, and move with a velocity of from one tenth to one third that of light. It is supposed that each particle carries a negative charge of electricity equal to that of the hydrogen atom in electrolysis.

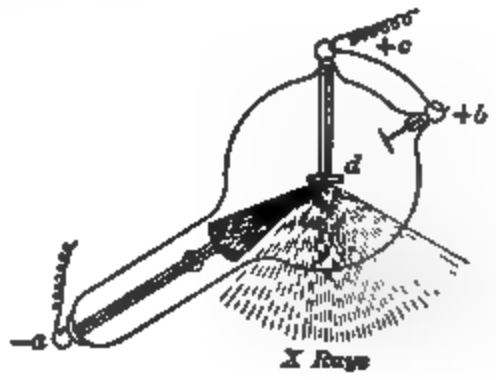


Fig. 577. Roentgen, or X-ray, tube.

506. Roentgen, or X, rays. In 1895, while experimenting with a vacuum tube, Roentgen discovered another kind of rays, which he called X rays. When cathode rays strike against a platinum target, as shown in figure 577, Roentgen rays are sent off from this target. They affect a photographic plate somewhat as sunlight does; but, like cathode rays, they will penetrate many substances opaque to ordinary light, such as wood, pasteboard, and the human body That they are not the same as cathode rays is shown by the fact that they are not deflected by a magnet.

When a photographic plate, inclosed in the usual plate-holder with sides of hard rubber or pasteboard, is exposed, with a hand held over it, to Roentgen rays, a shadow picture like that seen on the fluorescent screen is formed (Fig. 578).

Fig. 578. Radiograph of a hand.

We may demonstrate the action of Roentgen rays by operating an X-ray tube with an induction coil, and holding a fluorescent screen in

front of the bulb. If the room is dark and the hand is interposed between the tube and the screen, the flesh, which is easily penetrated by the rays, will be seen faintly outlined, while the bones will cast a strong shadow. Such a radiograph of the teeth is very valuable to the dentist in locating an abscess on the root of a tooth.

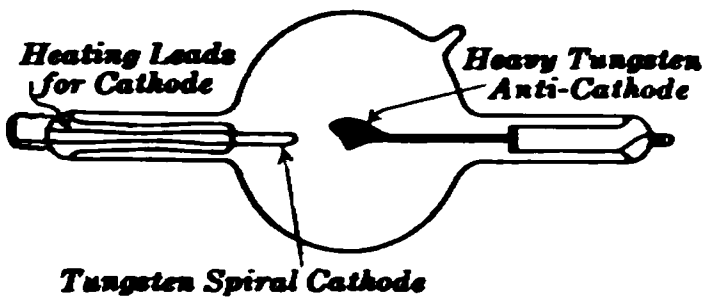


Fig. 579. Coolidge X-ray tube.

Roentgen, or X, rays are produced at and sent forth from any solid body on which cathode rays fall. They are now known to be *ether waves*, just like light waves, but of very much shorter wave length.

The penetrating power ("hardness") of X rays is increased by diminishing the gas pressure within the tube and by increasing the voltage across the electrodes. The Coolidge X-ray tube (Fig. 579) is exhausted so completely that it is impossible to send a discharge through the tube. To get the necessary electrons, an incandescent cathode is employed. This consists of a tungsten spiral heated by a subsidiary electric current from a 12-volt storage battery. The tungsten wire is surrounded by a molybdenum tube, which serves to focus the stream of electrons on the anticathode, which is also made of tungsten. The intensity of the X rays is precisely and readily controlled by adjusting the temperature of the cathode.

507. Radioactivity. In 1896, Henri Becquerel, in Paris, discovered that something resembling X rays is radiated by pitch blende and other minerals that contain the element uranium. He found that if a photographic plate, wrapped in black paper, is placed close to one of those minerals, a shadow photograph of an intervening coin or other dense object is formed. This phenomenon is called radioactivity.

508. How radium is obtained. Soon after, M. and Mme. Curie (Fig. 580), also in Paris, found that thorium, which, next to uranium, is the heaviest element known, possessed the same property. They were, however, astonished to find that pitch blende from a certain locality in Austria showed more radioactivity than an equal weight of either pure uranium or

pure thorium. It was thus made evident that this particular pitch blende contained some other substance far more radioactive than either uranium or thorium. After long months of arduous work, Mme. Curie succeeded in separating a minute quantity of this new substance in a fairly pure state from many tons of pitch blende. It proved to be a hitherto unknown chemical element, which she named **radium**. It has a radioactivity a million times that of an equal weight of the pitch blende in which it was first found, and is four million times as active as pure uranium.

Most of the radium now being produced in the world comes from a certain kind of ore found in Colorado. It takes 500 tons of this ore, and 500 tons of chemicals used in treating it, to say nothing of the quantities of coal for heating and of water for dissolving and washing, to produce a single gram of radium, and skilled men have to put in much work besides; so that it is no wonder that radium costs $100,000 a gram.

Fig. 580. Mme. Curie at work in her Paris laboratory.

Radium is ordinarily sold and used, not in its pure or metallic form, but combined with bromine in the form of a salt that looks very much like common salt. The salt containing a gram of radium weighs about 1.7 grams.

509. Uses of radium. The radiations given off by radium are extremely active. It is possible with their aid to take pictures in exactly the same way as with X rays. Radium

rays exert a very powerful action on living matter, and this has led to the hope that they will be useful in curing various diseases; indeed in treating certain kinds of cancer and similar growths radium seems to be very beneficial. Radium, which is extremely expensive, is continually producing radium emanation, and it is the emanation instead of the radium itself that is commonly used in treating diseases. Every day the emanation is pumped off from the radium salt and collected in very tiny glass tubes. These tubes are then inserted in the flesh near the cancer. Their curative power results from the fact that these rays kill diseased tissue much faster than they kill healthy tissue.

Certain radioactive elements in an impure condition have been used in the manufacture of **luminescent paint.** They are mixed with zinc sulfide, which fluoresces when in contact with radium particles. Luminescent paint makes watch and clock faces glow in the dark; and little buttons covered with it help to locate light switches or doorknobs at night.

510. Energy of radium. One of the most remarkable properties of radium and its salts is that they are continually producing **heat** and are generally three to five degrees warmer than their surroundings. Careful experiments show that one gram of radium gives off 100 calories per hour. This evolution of heat, although at a slow rate, continues for so long a time before a gram of radium is completely disintegrated, that the total heat which the gram will produce in its long life is nearly 300,000 times as much as a gram of coal produces when it is burned.

These facts are, in themselves, of no practical importance from the point of view of the energy needed in commerce and industry, because radium is so rare and so expensive. They make it plain, however, that inside the atoms of all substances, including coal itself, there must be stores of potential energy so vast in comparison with our ordinary heats of combustion as to be of overwhelming importance, if we could only learn how to set them free.

Unfortunately, however, even in the case of radium, the

rate at which this energy is set free has been found to be exactly the same at the extreme cold of liquid air as at ordinary temperatures, and to be entirely unaffected by anything that we can do to the radium; that is, it is entirely **uncontrollable.** Who shall say, however, what the future has in store?

SUMMARY OF PRINCIPLES IN CHAPTER XXIII

Ether waves **are set up by an electric spark; they were first detected by Hertz.**

Discharge of a condenser through a circuit of small resistance is *oscillatory*.

Two electric circuits so tuned as to have the same frequency are said to be in *resonance*.

Crystal detectors and vacuum-tube detectors act as *rectifiers*. The latter may also act as *amplifiers*.

In *radio telegraphy* electric waves are sent from an aërial, transmitted through the ether, and received by another aërial connected with a detector and telephone.

In *radio telephony* undamped continuous oscillations of very high frequency are modified in intensity by the varying resistance of the transmitter. Receiving station like that used for radio telegraphy.

Cathode rays **are streams of negatively electrified particles, called *electrons*, shot off from the cathode surface.**

Roentgen*, or *X*, *rays **are produced where cathode rays strike a solid object or target. They pass through glass and affect a photographic plate. They penetrate different materials approximately *inversely* as the densities of the materials These rays are identical with ultra-violet light of extremely short wave length.**

Radioactive substances **emit spontaneously rays which are similar to X rays. Radium evolves *heat* slowly but continuously.**

Questions

1. What is the relation between the length and frequency of an electric wave?

2. What evidence have we for thinking that an electric spark starts a series of ether waves?

3. What is the function of the aërial wires used in radio stations?

4. What advantages has the International Morse code over the ordinary Morse code?

5. What is the experimental evidence for believing that cathode rays are negatively charged particles, and not ether waves?

6. What is the experimental evidence for believing that X rays are extremely short waves, similar to but shorter than the ultra-violet light rays?

7. How is radioactivity different from the usual chemical action?

8. How could one test the activity of a radioactive substance?

Practical Exercises

1. **Radio station.** Set up a telegraph key with a dry cell and buzzer. Learn the International code. Then construct and operate a simple receiving and sending apparatus. Improve your outfit as you become more proficient in its use and understand its working.

2. **Radioactivity.** Wrap a photographic plate in black paper. Lay a Welsbach mantle on the paper next to the film side of the plate. Flatten it down and leave the whole in a light-tight box for a week. Then develop the plate. A picture of the mantle will appear on it.

3. **Ignition testers.** A device for testing the ignition system of an automobile has recently appeared, which consists of a hard-rubber case containing a glass tube. When the device is held near a spark plug that is working well, the glass tube glows with a bright orange light. Find out how such a device is made and how it works. What is in the glass tube? What makes it glow? Find out how useful such devices are found to be in practice.

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